# SIZE DISTRIBUTION AND EMISSION RATE MEASUREMENTS IN THE INCO SUPERSTACK CHIMNEY AND IRON ORE RECOVERY PLANT STACK PLUMES, 1979-1980.

SES 004/82

FALL 1982

The Honourable
Keith C. Norton, Q.C.,
Minister

Leonard J. M. Raymond
Deputy Minister

SUDBURY ENVIRONMENTAL STUDY

# SIZE DISTRIBUTION AND EMISSION RATE MEASUREMENTS OF PARTICULATES IN THE INCO 381 M CHIMNEY AND IRON ORE RECOVERY PLANT STACK PLUMES, 1979 - 80.

SES 004/82

by

Walter H. Chan and Maris A. Lusis
Special Studies Unit
Technology Development and Appraisal Section
Ontario Ministry of the Environment
880 Bay Street, 4th Floor
Toronto, Ontario, Canada, M5S 1Z8

and

R. Vet
Environmental Consulting
15 Euclid Street
Unionville, Ontario, Canada, L3R 1P5

and

Gregory B. Skelton
Skeltech
517-1276 Islington Ave.
Islington, Ontario, Canada, M9A 3J9

October 1982

S.E.S. Coordination Office
Ontario Ministry of Environment
6th Floor, 40 St. Clair Ave. W.
Toronto, Ontario, Canada, M4V 1M2
Project Coordinator: E. Piché

SES 004/82
ISBN 0-7743-7765-8
ARB-62-80

TABLE OF CONTENTS


| | | | Page |
|---|---|---|---|
| List of Tables | | | i |
| List of Figures | | | iii |
| Acknowledgements | | | v |
| Summary and Conclusions | | | vi |
| 1. | INTRODUCTION | | 1 |
| 2. | EXPERIMENTAL | | 2 |
| 3. | DATA PRESENTATION | | |
| | 3.1 | Flight Data | 4 |
| | 3.2 | Emission Data | 4 |
| | 3.3 | Chemical Analysis Results | 5 |
| | 3.4 | Data Precision | 5 |
| 4. | RESULTS AND DISCUSSION | | |
| | 4.1 | Particle Sizing Experiment | 7 |
| | | 4.1.1 INCO 381 M Chimney Results | 7 |
| | | 4.1.2 INCO IORP Results | 8 |
| | | 4.1.3 Comparison of 381 M Chimney and IORP Data | 9 |
| | | 4.1.4 Comparison of Airborne and In-Stack Data | 9 |
| | 4.2 | Pollutant Emission Rate Estimates | 10 |
| | | 4.2.1 INCO 381 M Chimney | 10 |
| | | 4.2.2 IORP Stack | 13 |
| | | 4.2.3 Airborne vs. In-Stack Measurements | 16 |
| References | | | 18 |
| Tables | | | 19 |
| Figures | | | 44 |
| Appendix 1 Estimates of INCO IORP Stack Emission Rates | | | 99 |

## LIST OF TABLES


| Table | | Page |
|---|---|---|
| 1 | Mass Median Diameter (um) of Particulate in the INCO 381 M Chimney Plume by Andersen Sampling | 19 |
| 2 | Summary of Modal Diameter (um) from Airborne Sampling in the INCO 381 M Chimney Plume | 20 |
| 3 | Mass Median Diameter (um) of Particulate in the INCO IORP Stack Plume by Andersen Sampling | 21 |
| 4 | Summary of Modal Diameter (um) from Airborne Sampling in the INCO IORP Stack Plume, 1980 | 22 |
| 5 | Comparison of Mass Median Diameter (um) of Particulates Determined by In-Stack and Airborne Measurements at the INCO 381 M Chimney in 1980 | 23 |
| 6 | Summary of Calculated INCO 381 M Chimney Emission Rates Using 47 mm Filter Packs (kg/day) | 24 |
| 7 | Estimated Average Emission Rates of Particulate from INCO 381 M Chimney (kg/day) | 25 |
| 8 | INCO 381 M Chimney Plume Studies (Sept. 1979 and Feb. 1980) Particulate-to-$SO_2$ Ratio Data-Linear Correlation Coefficients | 26 |
| 9 | INCO 381 M Chimney Plume Studies (Sept. 1979 and Feb. 1980) Concentration Data-Linear Correlation Coefficients | 27 |
| 10 | Summary of Calculated INCO IORP Stack Emission Rates Using 47 mm Filter Packs (kg/day) | 28 |
| 11 | Summary of Estimated INCO IORP Stack Emission Rates for Individual Processes | 29 |
| 12 | Estimated Average Emission Rates from INCO IORP Stack (kg/day) | 30 |
| 13 | Comparison of Airborne and In-Stack Measured Emission Rates (kg/day) of the INCO 381 M Chimney (1980) | 31 |
| A1 | Flow Volume (l) From Individual INCO 381 M Chimney Plume Flights | 32 |
| A2 | Flow Volume (l) for Individual INCO IORP Plume Flights | 33 |
| A3 | Estimated $SO_2$ Emission Rates of INCO 381 M Chimney | 34 |
| A4 | Summary of INCO IORP Stack Emission Sources During Sampling | 35 |
| A5 | Summary of (M/Vol) Ratios in INCO 381 M Chimney Plume Using 47 mm Filter Packs | 36 |

LIST OF TABLES - continued


| Table | | Page |
|---|---|---|
| A6 | Summary of M/$SO_2$ Ratios in INCO 381 M Chimney Plume Using 47 mm Filter Packs | 37 |
| A7 | Summary of (M/Vol) Ratios in INCO IORP Stack Plume Using 47 mm Filter Packs | 39 |
| A8 | Summary of M/$SO_2$ Ratios in INCO IORP Stack Plume Using 47 mm Filter Packs | 40 |
| A9 | Summary of Total (M/Vol) Ratios in INCO 381 M Chimney Plume Using Andersen Sampler | 41 |
| A10 | Summary of Total (M/Vol) Ratios in INCO IORP Plume Using Andersen Sampling | 42 |
| A11 | Total Mass Emitted from IORP Stack During Airborne Sampling Periods | 43 |

## LIST OF FIGURES


| Figures | | Page |
|---|---|---|
| | Size Distribution Results of INCO 381 m Chimney | |
| 1. | Fe | 44 |
| 2. | Cu | 45 |
| 3. | Ni | 46 |
| 4. | Pb | 47 |
| 5. | Zn | 48 |
| 6. | Al | 49 |
| 7. | Cr | 50 |
| 8. | Cd | 51 |
| 9. | Mg | 52 |
| 10. | As | 53 |
| 11. | $SO_4$ | 54 |
| 12. | $NH_4$ | 55 |
| 13. | Se | 56 |
| 14. | Mn | 57 |
| | Modal Distribution Results of INCO 381 m Chimney | |
| 15. | 1979 Results - Zn, Fe, Ni, Cu and $SO_4$ | 58 |
| 16. | 1979 Results - $NH_4$, Cd, Mn, Al and Pb | 59 |
| 17. | Fe | 60 |
| 18. | Cu | 61 |
| 19. | Ni | 62 |
| 20. | Pb | 63 |
| 21. | Zn | 64 |
| 22. | Al | 65 |
| 23. | Cr | 66 |
| 24. | Cd | 67 |
| 25. | Se | 68 |
| 26. | As | 69 |
| 27. | Mg | 70 |
| 28. | $SO_4$ | 71 |
| 29. | $NH_4$ | 72 |

## LIST OF FIGURES - continued

Page

Figures

Size Distribution Results of INCO IORP Stack

30. Fe 73
31. Cu 74
32. Ni 75
33. Pb 76
34. Zn 77
35. Al 78
36. Cr 79
37. Co 80
38. Cd 81
39. Mg 82
40. As 83
41. $SO_4$ 84
42. $NH_4$ 85

Modal Distribution Results of INCO IORP Stack

43. Fe 86
44. Cu 87
45. Ni 88
46. Pb 89
47. Zn 90
48. Al 91
49. Cr 92
50. Co 93
51. Cd 94
52. Mg 95
53. As 96
54. $SO_4$ 97
55. $NH_4$ 98

## ACKNOWLEDGEMENTS

Thanks are due to the following persons whose contributions have made the studies possible:

Dr. D. Lake of Cambrian College for making available laboratory space during these studies; Messrs. S. Onlock and R. Regier for technical assistance; Messrs. L. Fitz, T. Van Rossum, J. Bassett, D. Bazinet and F. Lalonde for process documentation; Messrs. R. Chiu, R. Regier and M. Talbot for some calculations and preparation of figures; J. McDonald for helpful discussions; Mr. F. Tomassinni and Dr. B. Loescher for coordinating laboratory analyses and Messrs L. Fitz and R. Potvin for critical comments on the report.

## SUMMARY AND CONCLUSIONS

In September, 1979 and February, 1980, airborne studies were carried out in the INCO 381 m chimney, and Iron Ore Recovery Plant (IORP) Stack plumes to determine the size distribution of the plume particulate constituents, and their emisison rates, using an instrumented helicopter. The following conclusions can be drawn from this work.

- Particulates emitted from the INCO 381 m stack can be classified into coarse (greater than 2.5 um) and fine (less than 2.5 um) size ranges. Fe, Cu, Ni, Al, Mg and Mn are predominantly in the coarse particles, while Pb, Zn, As, $SO_4$, $NH_4$ and Se are predominantly in the fine size range. On one day of atypical emissions (Feb. 5, 1980), when particulates were visually observed to be settling out near the stack, mass median diameters (MMD) of most species were found to be greater than on other days.

- A relatively large variation of the particle emission rates for some trace metals was observed from the INCO 381 m stack. The major emittants are (expressed in kg/day for the Sept. 1979 and Feb. 1980 studies respectively): $SO_4$ (25936/31935), Si (2711/-), Fe (674/704), Cu (624/287), Pb (266/440), Ni (120/270), As (103/153) and Zn (81/53). The accuracy of the emission rates should be typically within a factor of two.

- In the case of the IORP stack emissions, particulate size seems to depend on the operating conditions in the Copper Cliff Nickel Refinery (CCNR). When only the IORP + CIL flues are emitting, the plume consitutents can be classified into coarse particles - Fe, Cu, Ni, Al and Cd and fine particles -

$SO_4$ and $NH_4$. In general, the metal particulates appear to be smaller when the Nickel Refinery is in operation with IORP + CIL whereas the reverse applies to $SO_4$ and $NH_4$. The size distribution of IORP emittants differs quite significantly from that of INCO 381 m chimney. MMD's of Fe, Cu, Ni, Al and Cd are lower in IORP compared to those of the 381 m chimney whereas those of Pb, Zn, Cd, As, $SO_4$ and $NH_4$ show the reverse pattern.

- The major emittants from IORP are (expressed in kg/day): $SO_4$ (9220), Fe (787), Ni (520), Cu (187) and Pb (39). The accuracy of the emission rates is not expected to be better than a factor of two. It is interesting to note that the IORP stack emissions of Fe and Ni could be comparable or higher than the corresponding values from the 381 m chimney. Emissions of $SO_4$ and $SO_2$ from the IORP stack occur predominantly during the Copper Cliff Nickel Refinery (CCNR) Blow phase and those of Cu and Ni during the CCNR Charge phase. It should be noted that, with the installation of the new electrostatic precipitator, the particulate emissions are considerably reduced. Emissions of Fe are quite uniform throughout the 3 different phases of the CCNR operation and the background IORP + CIL operation.

## 1. INTRODUCTION

In September, 1979 and February, 1980, the Special Studies Unit of the Air Resources Branch carried out two airborne particle sampling studies in the INCO 381 m chimney and IORP stack plumes in the Sudbury area. In the first study, only the 381 m stack plume was sampled. In the second study, sampling was done both in the 381 m chimney and the Iron Ore Recovery Plant (IORP) stack plumes.

The purpose of these studies was similar, in that they were both designed to measure the chemical composition of plume particulates as a function of size, and to determine emission rates of various particulate constituents. Such data, especially from the IORP, were very limited. Apart from their obvious relevance to health effects, particle size data were needed in order to better evaluate deposition rates for the different pollutants emitted by these individual sources.

## 2. EXPERIMENTAL

Both the airborne experimental equipment and chemical analytical procedure used are similar to those in previous airborne studies in the Sudbury Falconbridge stack plume (1). However, a brief description is also given here.

The airborne sampling platform consisted of a Hughes 500 C helicopter instrumented with both an Andersen Cascade Impactor and a 47 mm low volume filter sampling packs mounted on both the port and starboard sides of the aircraft. Sticky (coated with a solution of petroleum jelly in toluene) and non-sticky polyethylene substrates were used in the Andersen samplers on the 8 stages for the collection of trace metal and non-trace metal particulates respectively. These stages were followed by a Whatman 40 backup filter to collect particles less than about 0.4 um. Each of the 47 mm packs consisted of a Whatman 40 pre-filter for particulate sampling followed by 3 pairs of Whatman 41 filters impregnated with potassium carbonate ($K_2CO_3$) -glycerol for $SO_2$ sampling.

Sampling was carried out by flying along the plume axis towards the chimney, starting at about 2-3 km downwind. An air speed was chosen such that isokinetic sampling could be maintained.

After sampling, filters were stored in polyethylene bags and transferred to the Toronto laboratory for chemical analysis. Both aqueous and acid leachings were carried out at different stages as part of the extraction procedures for the analysis of $SO_4^=$, $NH_4^+$ and $NO_3^-$, and trace metals. Due to low loadings of $NO_3^-$, $NH_4^+$ and Al compared to the filter blank, very few data for these parameters were available for inclusion in this report. $SO_2$ filters were extracted with 0.05% $H_2O_2$ before chemical analysis in the form of $SO_4^=$. Trace metals were determined by flameless atomic absorption spectroscopy and the other non-metal

species by ion-exchange chromatography ($SO_4^=$ and $NO_3^-$) and phenate hypochlorite ($NH_4^+$) methods. Due to the methods used in aliquoting extracts, trace metals results could potentially have a systematic error toward the low side of 10% and 5% respectively for the September and February studies.

## 3. DATA PRESENTATION

### 3.1 Flight Data

In the September Study, three runs, each lasting about 1 - 1½ hours, were carried out during the one day of sampling in the INCO 381 m chimney plume. In the February Study, due to the need for synchronizing the airborne measurement with the in-stack measurement of the 381 m stack, and because of the batch mode nature of the IORP-Nickel Refinery plant production, only two runs per day were carried out.

The sampling of the INCO 381 m chimney plume was relatively straight-forward. However, the IORP stack emissions consist of flue gases from three sources, i.e. IORP plant, CIL acid plant and the Nickel Refinery plant. The former two plants normally operate continuously but the Nickel Refinery operates through a 3-stage cycle, namely charge, blow and reduction. On the average, these stages last for approximately 2 hours, 1½ hour, and 2 hours respectively (as indicated by INCO Ltd). The long-term emission rate from IORP can be estimated using experimental data for the above individual process stages.

Data on plume volumes sampled during these runs are summarized in the Appendix as Tables A1 and A2 for the INCO 381 m chimney and IORP stack plumes respectively.

On September 10, 1979 and February 6, 1980, background air was sampled well clear of the plumes with the same instrumentation package. It was found that the background contributions of the various parameters of interest were negligible and therefore no background correction was necessary in the loading calculations presented in this report.

### 3.2 Emission Data

During the sampling periods, an Abatement Officer from the North-

eastern Region of MOE was present in the INCO plant to document operations. Based on $SO_2$ continuous monitor data (fdor 381 m chimney) and mass balance calculations (for IORP), $SO_2$ emission rates from the INCO 381 m chimney and IORP stack during the sampling period were estimated, and these results are given for the two sources in Tables A3 and A4 of the Appendix.

As will be seen later, these $SO_2$ emission data are used in the calculations of particulate emission rates. The accuracy of the final results depends strongly on the accuracy of these input data.

### 3.3 Chemical Analysis Results

All results are expressed in terms of either average plume concentrations or parameter-to-$SO_2$ concentration ratios. In the case of 47 mm filter pack, only values corresponding to sample loadings equal to or greater than two times the filter blank values are included. However in the case of Andersen sizing data, because of the relatively low loadings on individual substrates, all data except those which were less than detection limits are included. The 47 mm and Andersen results are summarized in Tables A5 to A8 and A9 to A10 respectively in the Appendix. Because of their higher loading to blank ratios, only the 47 mm data were used for emission rate calculations.

### 3.4 Data Precision

To ensure the quality of the data used in this report, it is desirable to examine the precision of the measurements.

In the case of 47 mm filter pack sampling, measurements from the Port and Starboard samplers were compared. In general, the agreement was within $\pm$ 30% which is considered to be fully satisfactory.

Contrary to the previous studies in the Falconbridge stack plume (1), in the current study more material per unit volume sampled was generally collected in the Andersen impactors than the 47 mm filter packs, the difference often being in excess of 50%. The discrepancy seems to be worst for Pb, Cd, Fe and Zn. The reason for this occurrence is not clear especially since the comparison for $SO_4$ was excellent.

# 4. RESULTS AND DISCUSSION

## 4.1 Particle Sizing Experiment

### 4.1.1 INCO 381 M Chimney Results

Because of the particle bounce problem referred to in an earlier report (1), most trace metals were determined on sticky substrate samples. Non-sticky substrates were used to analyze for $SO_4^=$, $NH_4^+$ $NO_3^-$, As and Se. Particle bounce is not as much of a problem with the latter group of parameters as they exist in the fine particle size range.

The mass median diameters (MMD) of the various species are given in Table 1. Data collected in September, 1979 and February, 1980 are, in general, quite consistent except in the cases of Fe, Al, $SO_4^=$ and $NH_4^+$. In these cases, the MMD appeared to be larger in the February study but due to the limited sample size, it is difficult to attach any significance to this change. There seems to be considerable variability from one sample to another in the MMD of Cu, Al, Cr and Cd. The data can be broadly categorized into two classes: Fe, Cu, Ni, Al, Mg and Mn belong to the coarse particle range with MMD larger than 2.5 um; and Pb, Zn, Cr, Cd, As, $SO_4$, $NH_4$, and Se belong to the fine particle size range, with MMD less than 2.5 um.

The cumulative size plots are shown in Figures 1 to 14. Generally, the distributions do not follow a log-normal pattern, but tend to be bimodal, as shown in the differential plots on Figures 15 to 29. The modal diameters are summarized in Table 2. Aside from the modes below 5 um, there is some indication that a mode larger than 9 um exists for some of the heavy metals. It should be noted that on February 5, 1980, particle fall out was observed near the stack. The MMD's so determined (except for particles with MMD greater than 9 um) are larger for this date compared to other runs and should be considered as atypical.

4.1.2 INCO IORP Results

The corresponding results obtained from the IORP plume are summarized in Tables 3 to 4 and Figures 30 to 55.

The 3 sets of Andersen samples represent sizing information on the different stages of the Nickel Refinery operation. As mentioned in Section 3.1, the IORP stack plume consists of flue gases from the IORP plant, CIL acid plants and the Nickel Refinery plant. Both the IORP plant and CIL plants operate on a continuous basis contributing to the background flue. The Nickel Refinery plant operates on a batch mode, each cycle consisting of the blow, reduction and charge stages. The 3 Andersen samples correspond to (i) Feb. 1, 1980 -Reduction stage of the Nickel Refinery plant in addition to the regular IORP/CIL background operations; (ii) Feb. 2/3, 1980 - A prorated complete cycle of the Nickel Refinery, IORP and CIL operations; and, (iii) Feb. 8, 1980 -Nickel Refinery not operating, only background flues from IORP and CIL plants.

As seen in Table 3, the nature of the emitted particles is rather different when Nickel Refinery emissions are present, especially in the cases of Cu, Al, Cd, $SO_4^=$ and $NH_4^+$. It appears that metals emitted from the IORP + CIL are generally larger than those from the IORP + CIL & the Nickel Refinery. This is consistent with the fact that the CCNR flue passes through electrostatic precipitator but the IORP main balloon flue has only hoppers and CIL does not contribute to particulates. However, $SO_4^=$ and $NH_4^+$ from IORP + CIL appear to be smaller. When the Nickel Refinery is emitting, the size distributions of most elements appear to be roughly equivalent regardless of the phase of plant operations and this is probably related to the capture efficiency of the electrostatic precipitator. Only Ni appears to be an exception to this.

4.1.3 Comparison of 381 M Chimney and IORP Data

There are definite differences in the size ranges of the emitted particles from the two sources. The distinction between the composition of the coarse and fine particles in the 381 m chimney source is quite obvious but the particles in different size ranges emitted from the IORP stack are much more similar in chemical composition. Of particular interest is the $SO_4^=$ MMD's at the two sources, which suggest that the $SO_4^=$ emitted from the IORP stack should have a higher deposition velocity than that from the 381 m stack, and this, together with the fact that the IORP stack is shorter, has signficant implications on the relative contribution to the deposition of acidifying materials from the two sources.

4.1.4. Comparison of Airborne and In-Stack Data

During the February, 1980 airborne study, in-stack particle sizing experiments were also carried out in the 381 m stack by the Air Resources Branch's Source Assessment Unit (see reference 4). Even though the sampling periods did not coincide, a comparison of these data was attempted.

Particle sizing results for some selected parameters are summarized in Table 5. The results for the coarse particles, i.e. Fe, Ni, and Cu, are consistent for the plume and in-stack samples. There is some indication that the volatile metal bearing particulates (i.e. Pb and Zn) grow slightly or remain fairly constant in size upon release from the stack. However, in the case of $SO_4$, a reverse pattern is suggested. This observation, which was also made in the case of Falconbridge Studies(1), can be attributed to the fact that the in-stack

sampling train collects preferentially non-volatile metal sulfates but not all the sulfuric acid which exists mainly as $SO_3$ vapor due to the high sampling temperature. This could, in part, explain the larger MMD of the sample. Under airborne sampling conditions at ambient temperature, sulfuric acid will be in the form of an aerosol in the fine particle size range, and will be collected without loss on the substrate, leading to the observed lower mass median diameters for sulfate.

## 4.2 Pollutant Emission Rate Estimates

### 4.2.1 INCO 381 M Chimney

In Tables A5 and A6, 47 mm filter pack sampling results are summarized in the form of plume concentration, and particulate-to-$SO_2$ ratios. It is noted that the particulate-to-$SO_2$ ratios are in good agreement with those reported previously (2). Using the "Ratio Method" (3), emission rates of these species can be obtained by multiplying the ratio of particulate-to-$SO_2$ with $SO_2$ emission rates and the results are given in Table 6. Two methods described elsewhere (1) are used for calculating the long term emission rates which are given in Table 7 - the first one corresponds to the average of the individual emission rates during individual runs, while the second one employs the average $M/SO_2$ ratio and average $SO_2$ emission rate obtained from continuous monitor for the overall period of the calculations. The two formulae are given below:

Method 1:
$$\frac{\sum_{i=1}^{n}\left[\left(\frac{M}{SO_2}\right) \times (SO_2)_{E.R.}\right]_i}{n} \qquad (1)$$

and

Method 2: $$\left[\frac{\sum_{i=1}^{n}\left(\frac{M}{SO_2}\right)_i}{n}\right] \times \left[\frac{\sum_{i=1}^{n}(SO_2)_{i,E.R.}}{n}\right] \qquad (2)$$

where n = the number of runs

i = individual run number

ER = emission rate

In general, the agreement between the two methods was quite good. It is felt that the accuracy of the emission rates should be typically within a factor of two.

Since the emissions from the February 5 run were atypical, only data from other sampling dates were combined to obtain average long term emission rates. Calculations of emission rates based on the February 5 data were also made and they can be considered as first lower estimate of emission rates for days with particle fall-out. It is noted that emissions of Fe, Cu, Ni and Se were much higher for this date.

Emission rates based on the 2 methods are summarized in Table 7. The major emittants are $SO_4$, Si, Fe, Cu, Ni, Pb and As. It is seen that run-to-run variation is not so large but variation between studies (September and February) can be considerable for some metals (Se, Mn, Cd). Again, it must be remembered that the September results are based on only one sampling day.

Tables 8 and 9 summarize the linear correlation coefficients of particulate-to-$SO_2$ ratios as observed on the 47 mm filters, and also average plume concentrations. In both cases, the cross correlation of the data with the continuous monitor $SO_2$ emission rate is also examined. The former takes into account the $SO_2$ production and the latter shows the absolute relationship among the various parameters. Only correlation coefficients which are significant at the 99% confidence level are printed.

The correlation between the particulate-to-$SO_2$ data is in general not statistically significant. The correlation between the concentration data should indicate whether the various parameters are emitted in the same fashion, i.e. whether the inter-elemental emission ratios remain constant. The heavy metals Fe, Cu and Ni correlate quite highly. This is not surprising in view of the smelter operation. The high correlation between $SO_4$ and the trace metals suggests that these parameters may be chemically associated. The high correlation between As, Se, Cd and the trace metals may reflect the high correlation between $SO_4$ and these metals and the fact that both As, Se, Cd and $SO_4$ are in the small size range. The latter argument also applies to the high correlation between $SO_2$ and Pb, Zn, Cd, As and $SO_4$. It should be noted that there is no significant correlation between the $SO_2$ emission rates and the measured loading of the various emittants.

4.2.2 IORP Stack

As previously stated, emissions from the IORP stack have three sources, namely, the IORP, the CIL acid plants, and the Copper Cliff Nickel Refinery (CCNR). Under normal operating conditions, the IORP plus CIL plants maintain a relatively constant emission rate. The CCNR however has variable emissions which depend on the operating phase of the two converters which exhaust to the stack and the consistency of the matte feed to the converters. Each converter follows a three phase process for each load of feed matte. The duration of these phases and their respective relative $SO_2$ and particulate emission rates (as estimated by INCO) are summarized below:

| Phase | Relative $SO_2$ Emission Rate | Relative Particulate Emission Rate | Average Time of Phase (hours) |
|---|---|---|---|
| Charge | 5 - 10% | 40% | 2 |
| Blow | 60 - 70% | 30% | 1.5 |
| Reduction | 10 - 30% | 30% | 2 |

Each converter can operate independently of the other with the exception that both cannot be in the blow phase simultaneously.

An attempt was made during the field study to control the mode of operation of the nickel converters; however it was not possible to control to the extent where emissions during each individual phase could be sampled. This meant that many of the airborne samples collected during the study contained combinations of phases and combinations of converters. A summary of the sampling conditions is given in Table A4.

The operating conditions (specified in Table A4) and the metal emission rates for each sampling flight (given in Table 10 as determined by the Ratio Method) were combined to produce estimates of the emission rates of metals for each individual process. The calculations, which assume that the overall process emission rate is a linear function of the individual contributing sources, are described in Appendix 1.

In brief, a system of 5 linear equations with 4 unknowns (i.e. emission rates) was set up. Four of the equations were used to calculate the emission rates and the fifth was used to check these calculations against a measured value.

The resulting emission rates estimated for the individual processes are summarized in Table 11.

A number of comments can be made based on Table 11. Care should be taken to consider these comments in light of the fact that the IORP & CIL processes are roughly continuous while the CCNR process emissions are intermittent.

a) The emissions from the IORP and CIL complex are dominated by $SO_4^=$ (3.58 kg/min) and Fe (0.34 kg/min). The emissions of Cu and Ni are an order of magnitude less than those of Fe and those of As and Pb are two orders of magnitude less.

b) The three CCNR processes produce emissions of different composition. For example, the largest $SO_4^=$ and $SO_2$ emission rates occurred during the BLOW phase while the largest Cu and Ni emission rates occurred during the CHARGE phase.

c) With the exception of Fe, the REDUCTION phase produced significantly smaller emissions of all parameters than the other phases

d) The emission rate of Ni during the CHARGE phase is significantly larger than the emission rate of any other metal during any other phase.

e) Emissions from the IORP & CIL complex are generally smaller than or comparable to the emissions from the CCNR CHARGE & BLOW phases (see numbers in brackets in Table 11).

The accuracy of the estimated emission rates given in Table 11 is very difficult to establish. The check on the data suggests that the estimates should in general be accurate within a factor of two. Note that this applies only to errors resulting from the assumptions involved in the calculations. In addition, there is an uncertainty in the results due to possible sampling errors and process variability with time. Thus, the factor-of-two estimate is probably a lower limit.

The estimates of emission rates for each of the individual sources contributing to the total emission from the IORP stack make it possible to estimate a long term average daily emission rate based on daily average operating conditions. The following assumptions were made for these calculations:

a) IORP + CIL emissions are constant for an average 24 hour day.

b) The CCNR operates 3 complete cycles (or heats) per average day.

c) The CHARGE, BLOW and REDUCTION phases last 2, 1.5 and 2 hours respectively during an average day.

d) The average emission rates for each process are equivalent to those in Table 11.

e) The average feedrate to the IORP, CIL and CCNR processes obtained during the airborne study represents the daily average feedrate.

The long term average daily (IORP + CIL), CCNR and total emission rates for the various chemical parameters are given in Table 12. The estimates indicate that emissions are dominated by $SO_4^=$ followed by Fe, Ni, Cu, Pb and As. Both the (IORP + CIL) and CCNR produce roughly equivalent emissions of $SO_4^=$ and Fe while the CCNR emits significantly greater amounts of Cu, Ni and As and only slightly greater amounts of Pb.

By assuming that the average $SO_2$ emission rate during the field study is representative of the long-term average, it was possible to calculate the average $SO_4^=/SO_2$ ratio for the total IORP stack emissions. For an estimated average $SO_2$ emission rate of $1.90 \times 10^5$ kg/day, the average $SO_4^=/SO_2$ ratio is 4.9%. However, the individual processes have very different ratios, namely, 3.7% for the IORP + CIL, 50.0% for CCNR CHARGE phase, 6.9% for the CCNR BLOW phase and 3.2% for the CCNR REDUCTION phase. The unusually large value for the CHARGE phase is due to the low $SO_2$ emission rate during this phase.

### 4.2.3 Airborne vs. In-Stack Measurements

During the February Study, attempts were made to obtain simultaneous airborne and in-stack measurements of the 381 m chimney emission rates. The in-stack measurements were joint efforts by MOE and INCO and are described elsewhere (4). Both multi-point and single-point measurements were made. Due to technical problems encountered by the in-stack team, only limited data are available for comparison. Table 13 summarizes the multi-point data obtained by the MOE team together with the airborne data.

It is seen that the comparison between the airborne and in-stack measurements is rather poor. Except in the cases of As and $SO_4$, the airborne samples indicate significantly lower emission rates than the in-stack ones. Emissions on Feb. 5 were atypical. There was evidence of in-stack stratification and large particle fallout during in-stack sampling. This could explain the lower emission rates of elements found in coarse particles as calculated from the airborne measurements (since part of the particulate sample was not collected, but had fallen out from the plume). The reason for Feb. 7 discrepancies is unknown. However, it should be borne in mind that there is some uncertainty about the $SO_2$ emission rates that were used in estimating emissions from the airborne results.

## REFERENCES

1. W.H. Chan, R.J. Vet, G.B. Skelton and M.A. Lusis, "Size Distribution and Emission Rate Measurements of Particulates in the 93 m Falconbridge Smelter Stack Plume, 1979" MOE-ARB-TDA Report #57-80 (1980)

2. "Airborne Investigations of the INCO and Falconbridge Stack Plumes, 1976-77" MOE-ARB-TDA report #60-79 (1979)

3. W.H. Chan, R.J. Vet, M.A. Lusis, J.E. Hunt and R.D.S. Stevens, "Airborne Estimation of Particulate Emissions from Stacks: A Feasibility Study", Atmos. Environ., 14 (10), 1201 (1980).

4. V. Ozvacic and J. McDonald, "Determination of the Extent of Particulate Stratification at the INCO 381 Meter Chimney at Copper Cliff, Ontario", MOE-ARB-TDA Report #58-80 (1980)

Table 1: Mass Median Diameter (um) of Particulate in the INCO 381 m Chimney Plume by Andersen Sampling

| PARAMETER | MASS MEDIAN DIAMETER (um) Sept. 8 1979 | Jan. 31 1980 | Feb. 4 1980 | Feb. 5* 1980 | Feb. 7 1980 |
|---|---|---|---|---|---|
| Fe | 5.2 | >9 | >9 | >9 | >9 |
| Cu | >9 | >9 | >9 | >9 | 2.8 |
| Ni | >9 | >9 | >9 | >9 | >9 |
| Pb | 1.0 | 1.05 | 0.92 | 1.7 | 1.15 |
| Zn | 1.1 | 1.1 | 0.96 | 6.6 | 2.1 |
| Al | 3.2 | 2.1 | 8.2 | >9 | 5.6 |
| Cr | - | 3.8 | 1.0 | - | - |
| Cd | 3.1 | 1.5 | 1.9 | 1.1 | 3.4 |
| Mg | - | 8.0 | >9 | >9 | 7.0 |
| As | - | 0.98 | 0.92 | 0.96 | 1.0 |
| $SO_4$ | 0.48 | 0.98 | 0.93 | 1.1 | 0.94 |
| $NH_4$ | 0.53 | 1.6 | 2.0 | 2.2 | 2.6 |
| Se | - | - | - | 1.25 | 1.4 |
| Mn | 4.2 | - | - | - | - |

* Emissions on this date were atypical. Particulate fallout near the stack was observed.

Table 2: Summary of Modal Diameter (um) from Airborne Sampling in the INCO 381 m Chimney Plume[+]

| | Sept. 8, 1979 | Jan. 31, 1980 | Feb. 4, 1980 | Feb. 5, 1980** | Feb. 7, 1980 |
|---|---|---|---|---|---|
| Fe | *, 3.3 | 1.1, 3.3 | 1.1, 3.3 | 3.3 | (1.1),3.3 |
| Cu | *, 3.3 | 0.7, 3.3 | 0.7, 3.3 | (0.4), 1.1 | (0.7), 2.1 |
| Ni | *, 3.3 | 3.3 | (0.7),3.3 | 2.1 | 3.3 |
| Pb | *, 3.3 | 0.7, 3.3 | 0.4, 1.1, 3.3 | 0.7 | 0.7, (2.1) |
| Zn | *, 2.1, - | 0.7, 3.3 | - | (0.4), 1.1 | 0.7, 2.1 |
| Al | *, 2.3, 4.2 | 1.1 | - | - | - |
| Cr | - | 0.7, 4.7 | - | - | - |
| Cd | *, 2.0, 4.9 | 0.4, 1.1, 3.3 | 0.4, 1.1, 4.7 | 0.7, 2.1 | 0.7, 3.3 |
| Mn | *, 3.5 | - | - | - | - |
| Se | - | - | - | 0.4, 1.1 | 2.1 |
| As | - | 0.7 | 0.7, 3.3 | 0.7 | 0.7 |
| Mg | - | 0.4, (3.3) | 0.7, 3.3 | 3.3 | 4.7 |
| $SO_4$ | 0.4, 4.5 | 0.4, (4.7) | 0.7, 4.7 | 0.7, 4.7 | 0.7 |
| $NH_4$ | (0.7), 4.5 | 0.7, (2.1), 4.0 | 0.7, 4.7 | 0.4, 2.1, 4.7 | 0.7, 4.7 |

+ There is evidence of a mode larger than 9 um for some heavy metals, but diameter cannot be defined due to sampler cut-off limits.

* Incomplete results due to loss of partial Andersen sample in the course of chemical analysis.

** Emissions on this date were atypical. Particulate fallout near the stack was observed.

Table 3: Mass Median Diameter (um) of Particulate in the INCO IORP Stack Plume by Andersen Sampling

| PARAMETER | MASS MEDIAN DIAMETER (um) | | |
|---|---|---|---|
| | Feb. 1, 1980 CIL + IORP + Reduction | Feb. 2/3, 1980 CIL + IORP + Blow + Reduction + Charge | Feb. 8, 1980 CIL + IORP only |
| Fe | 6.2 | 7.6 | 8.0 |
| Cu | 2.95 | 2.6 | 5.9 |
| Ni | 5.6 | 2.5 | 5.3 |
| Pb | 3.35 | 3.1 | - |
| Zn | 3.2 | - | - |
| Al | 0.68 | - | 8.4 |
| Cr | 3.0 | - | - |
| Co | - | 2.2 | - |
| Cd | 0.62 | 0.55 | 6.2 |
| Mg | 2.3 | 3.6 | - |
| As | - | 2.4 | - |
| $SO_4$ | 3.2 | 2.45 | 0.50 |
| $NH_4$ | 2.0 | 1.6 | 0.86 |

Table 4: Summary of Modal Diameter (um) from Airborne Sampling in the INCO IORP Stack Plume, 1980[+]

| | Feb. 1 | Feb. 2/3 | Feb. 8 |
|---|---|---|---|
| Fe | 0.4, 4.7 | (2.1), 3.3 | - |
| Cu | 0.4, 3.3 | 2.1 | (1.1), 3.3 |
| Ni | 0.7, 3.3 | 2.1 | 3.3 |
| Pb | 0.7, 3.3 | 0.7, 2.1 | - |
| Zn | 0.7, 4.7 | - | - |
| Al | 0.6, 4.7 | - | - |
| Cr | 0.7, 4.7 | - | - |
| Co | - | 2.1 | - |
| Cd | 0.4, 2.1, 4.7 | 0.4, 1.1, 3.3 | 0.4, 2.1, 4.7 |
| Mg | 0.4, 2.1 | 0.4, 3.3 | - |
| As | - | 1.8 | - |
| $SO_4$ | 2.1, 4.7 | 0.7, 3.3 | - |
| $NH_4$ | 0.7, 2.1, 4.7 | 0.7, 4.7 | 0.7, 4.7 |

[+] There is evidence of a mode larger than 9 um for some of the heavy metals, but diameter cannot be defined due to sampler cutoff limits.

Table 5: Comparison of Mass Median Diameter (um) of Particulates Determined by In-Stack and Airborne Measurements at the INCO 381 m Chimney in 1980

| | Parameter | | | | | |
|---|---|---|---|---|---|---|
| | Fe | Ni | Cu | Pb | Zn | $SO_4$ |
| In-Stack: | | | | | | |
| Jan. 30, 1980 | >13 | >13 | >13 | .84 | 3.6 | 4.0 |
| Feb. 1, 1980 | >13 | >13 | 8.7 | 2.7 | .92 | 1.9 |
| Feb. 2, 1980 | >13 | >13 | >13 | 6.2* | 8.0* | 3.7 |
| Airborne: | | | | | | |
| Jan. 31, 1980 | >9 | >9 | >9 | 1.05 | 1.1 | 0.98 |
| Feb. 4, 1980 | >9 | >9 | >9 | 0.92 | 0.96 | 0.93 |
| Feb. 5, 1980+ | >9 | >9 | >9 | 1.7 | 6.6 | 1.1 |
| Feb. 7, 1980 | >9 | >9 | 2.8 | 1.15 | 2.1 | 0.94 |

* Results look suspiciously high.

\+ Particle sizes probably atypical due to particle stratification and fall out.

Table 6: Summary of Calculated INCO 381 m Chimney Emission Rates Using 47 mm Filter Packs (kg/day)*

| DATE | RUN# | PORT/ STAR-BOARD | PARAMETER | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Fe | Cu | Ni | Pb | Zn | Cr | Cd | Mn | Co | Se | As | Mg | $SO_4$ | Si |
| Sept. 8 1979 | 1 | P | - | 481.7 | 96.34 | 385.0 | 96.3 | - | 866.7* | - | - | 24.1 | 72.3 | - | 31292 | - |
| | 2 | P | 442.7 | 407.5 | 123.9 | 213.0 | 70.8 | - | 17.8 | 17.8 | - | 8.9 | 88.6 | - | 20124 | - |
| | 3 | P | 1027.6 | 1333.2 | 166.0 | 195.0 | 111.1 | - | 27.8 | - | - | 22.3 | 111.1 | - | 28766 | - |
| | 1 | S | 673.6 | 437.7 | 96.2 | 335.8 | 48.2 | - | 24.1 | - | - | 22.3 | 144.3 | - | 39062 | - |
| | 2 | S | 457.8 | 330.4 | 110.0 | 238.1 | 73.3 | - | 9.2 | - | - | 14.7 | 100.8 | - | 20459 | - |
| | 3 | S | | | | | | | | | | | | | | 2711 |
| Jan. 31 1980 | 1 | P | 817.0 | 299.3 | 252.8 | 388.7 | 59.2 | - | 16.2 | - | - | 31.7 | 184.0 | - | 26832.3 | |
| | 2 | P | 961.8 | 350.6 | 394.7 | 519.2 | 75.1 | - | 37.8 | - | - | 90.0 | 274.9 | - | 29697.6 | |
| | 1 | S | 629.5 | 295.8 | 227.0 | 395.6 | 73.1 | - | 18.4 | - | - | 18.6 | 153.1 | - | 26316.3 | |
| | 2 | S | 1207.1 | 373.6 | 415.8 | 456.0 | 55.6 | - | 32.5 | - | - | 59.2 | 203.1 | - | 24716.1 | |
| Feb. 4 1980 | 1 | P | 789.5 | 368.6 | 444.6 | 787.8 | 68.4 | - | 24.9 | - | 10.6 | 6.0 | 110.6 | 47.9 | 33631.5 | |
| | 2 | P | 664.2 | 214.3 | 223.1 | 332.9 | 21.1 | 7.5 | 23.9 | - | - | 9.3 | 77.2 | - | 27116.7 | |
| | 1 | S | 820.1 | 297.2 | 327.1 | 785.5 | 67.0 | - | 24.9 | - | - | 6.9 | 106.0 | 35.2 | 31327.9 | |
| | 2 | S | 628.1 | 223.1 | 219.7 | 312.4 | 21.6 | - | 18.7 | - | - | 10.0 | 58.4 | - | 22825.9 | |
| Feb. 7 1980 | 1 | P | 459.0 | 332.6 | 200.3 | 385.1 | 61.7 | - | 17.7 | - | - | 77.6 | 147.8 | - | 47257.9 | |
| | 2 | P | 396.1 | 312.8 | 205.0 | 355.1 | 40.8 | - | 25.5 | - | - | 108.0 | 169.1 | - | 41427.7 | |
| | 1 | S | 414.2 | 305.3 | 159.5 | 359.8 | 61.7 | - | 18.4 | - | - | 68.3 | 202.3 | - | 46285.5 | |
| | 2 | S | 465.0 | 281.1 | 171.2 | 255.8 | 31.7 | - | 14.9 | - | - | 94.9 | 109.9 | 73.1 | 25786.6 | |
| Feb. 5 1980 | 1 | P | 1520.8 | 481.2 | 728.3 | 371.2 | 31.9 | 4.8 | 20.0 | 5.1 | 21.5 | 139.0 | 144.8 | 93.0 | 32876.0 | |
| | 2 | P | 832.4 | 293.1 | 326.1 | 534.6 | 42.5 | - | 21.6 | - | - | 132.0 | 104.7 | 36.66 | 33233.4 | |
| | 1 | S | 1586.1 | 435.5 | 685.8 | 313.5 | 32.7 | - | 20.3 | 3.7 | 18.2 | 179.0 | 133.9 | 82.0 | 31025.7 | |
| | 2 | S | - | - | - | - | - | - | - | - | - | - | - | - | - | |

* Only samples with loadings equal to or larger than 2x filter blank were included in calculations. * Not used in Table 7 calculations.

Table 7: Estimated Average Emission Rates of Particulates From the INCO 381 m Chimney (kg/day)

| Sampling Period | Number of Data Points | PARAMETER (M) Fe | Cu | Ni | Pb | Zn | Cr | Cd | Mn | Co | Se | As | Mg | $SO_4$ | Si |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Sept. 1979 | N | 4 | 5 | 5 | 5 | 5 | - | 4 | 1 | - | 5 | 5 | - | 5 | 1 |
| Method 1 | Ave. | 656.4 | 598.1 | 118.5 | 273.4 | 79.9 | - | 19.73 | 17.8 | - | 18.5 | 103.4 | - | 26141 | 2711 |
| | S.D. | 272.7 | 414.6 | 28.9 | 82.8 | 20.4 | - | 8.14 | - | - | 6.5 | 27.0 | - | 3415 | 1 |
| Method 2 | * | 674.3 | 624.1 | 119.6 | 265.8 | 80.6 | - | 20.21 | 17.2 | - | 18.6 | 102.6 | - | 25936 | 3177 |
| Jan. 31 and Feb. 4, 7/1980 | N | 12 | 12 | 12 | 12 | 12 | 1 | 12 | - | 1 | 12 | 12 | 3 | 12 | |
| Method 1 | Ave. | 700.3 | 304.5 | 270.1 | 444.5 | 53.1 | 7.5 | 22.8 | - | 10.6 | 48.4 | 149.6 | 52.1 | 31935.2 | |
| | S.D. | 229.4 | 49.8 | 99.3 | 173.1 | 19.4 | - | 6.9 | - | - | 38.7 | 61.2 | 19.3 | 8489.6 | |
| Method 2 | * | 731.2 | 287.4 | 269.8 | 439.9 | 53.2 | 8.5 | 22.9 | - | 9.0 | 48.1 | 152.5 | 46.1 | 32062.0 | |
| Feb. 5, 1980 | N | 3 | 3 | 3 | 3 | 3 | 1 | 3 | 2 | 2 | 3 | 3 | 3 | 3 | |
| Method 1 | Ave. | 1313.1 | 403.3 | 580.1 | 406.4 | 35.7 | 4.8 | 20.6 | 4.4 | 19.9 | 150.0 | 127.8 | 69.9 | 32378.5 | |
| | S.D. | 417.6 | 98.1 | 221.0 | 114.7 | 5.9 | - | .85 | .99 | 2.3 | 25.4 | 20.7 | 31.0 | 1185.1 | |
| Method 2 | * | 1400.76 | 426.1 | 623.5 | 401.2 | 35.8 | 5.4 | 21.0 | 5.2 | 22.6 | 155.7 | 134.1 | 75.6 | 33037 | |

* AVE $(M/SO_4)_1$ x AVE $(SO_4)_{E.R.}$

Table 8: INCO 381 m Chimney Plume Studies (Sept. /79 and Feb. /80) Particulate-to-$SO_2$ Ratio Data

Linear Correlation Coefficients
99% Confidence Level
(Number of Observation Points)

| | Fe | Cu | Ni | Pb | Zn | Cr | Cd | Mn | Co | Se | As | Mg | $SO_4$ | $SO_2$* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Fe | 1.000<br>19 | | | | | | | | | | | | | |
| Cu | | 1.000<br>20 | | | | | | | | | | | | |
| Ni | 0.953<br>19 | | 1.000<br>20 | | | | | | | | | | | |
| Pb | | | 0.593<br>20 | 1.000<br>20 | | | | | | | | | | |
| Zn | | 0.742<br>20 | | | 1.000<br>20 | | | | | | | | | |
| Cr | | | | | | 1.000<br>2 | | | | | | | | |
| Cd | 0.716<br>19 | 0.602<br>19 | 0.588<br>19 | | | | 1.000<br>19 | | | | | | | |
| Mn | | | | | | | | 1.000<br>3 | | | | | | |
| Co | | | | | | | | | 1.000<br>3 | | | | | |
| Se | 0.807<br>19 | | 0.863<br>20 | | | | 0.563<br>20 | | | 1.000<br>20 | | | | |
| As | | | | | | | | | | | 1.000<br>20 | | | |
| Mg | 0.926<br>6 | 0.963<br>6 | 0.939<br>6 | | | | | | | | | 1.000<br>6 | | |
| $SO_4$ | 0.673<br>19 | | 0.678<br>20 | | | | | | | 0.783<br>20 | | | 1.000<br>20 | |
| $SO_2$* | -0.76<br>19 | -0.59<br>20 | -0.65<br>20 | | | | | | | -0.61<br>20 | | | -0.59<br>20 | 1.000<br>20 |

* $SO_2$ emission rate based on continuous monitor data.

Table 9: INCO 381 m Chimney Plume Studies (Sept. /79 and Feb. /80) Concentration Data

Linear Correlation Coefficient
99% Confidence Level
(Number of Observation Points)

| | Fe | Cu | Ni | Pb | Zn | Cr | Cd | Mn | Co | Se | As | Mg | $SO_4$ | $SO_2$ | $SO_2$* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Fe | 1.000<br>20 | | | | | | | | | | | | | | |
| Cu | 0.846<br>20 | 1.000<br>21 | | | | | | | | | | | | | |
| Ni | 0.994<br>20 | 0.847<br>21 | 1.000<br>21 | | | | | | | | | | | | |
| Pb | 0.590<br>20 | | 0.606<br>21 | 1.000<br>21 | | | | | | | | | | | |
| Zn | | | | 0.718<br>21 | 1.000<br>21 | | | | | | | | | | |
| Cr | | | | | | 1.000<br>2 | | | | | | | | | |
| Cd | 0.765<br>20 | 0.673<br>20 | 0.753<br>20 | 0.826<br>20 | | | 1.000<br>20 | | | | | | | | |
| Mn | | | | | | | | 1.000<br>3 | | | | | | | |
| Co | | | | | | | | | 1.000<br>4 | | | | | | |
| Se | 0.832<br>20 | 0.811<br>21 | 0.824<br>21 | | | | 0.769<br>20 | | | 1.000<br>21 | | | | | |
| As | 0.596<br>20 | 0.613<br>21 | 0.633<br>21 | 0.559<br>21 | 0.564<br>21 | | 0.731<br>20 | | | 0.703<br>21 | 1.000<br>21 | | | | |
| Mg | | | | | | | | | | | | 1.000<br>7 | | | |
| $SO_4$ | 0.589<br>20 | 0.679<br>21 | 0.623<br>21 | 0.729<br>21 | 0.659<br>21 | | 0.796<br>20 | | 0.999<br>4 | 0.714<br>21 | 0.854<br>21 | | 1.000<br>21 | | |
| $SO_2$ | | | | 0.801<br>20 | 0.659<br>20 | | 0.727<br>19 | | | | 0.660<br>20 | | 0.820<br>20 | 1.000<br>20 | |
| $SO_2$* | | | | | | | | | | | | | | | 1.000<br>21 |

* $SO_2$ emission rate based on continuous monitor data.

Table 10: Summary of Calculated INCO IORP Stack Emission Rates Using 47 mm Filter Packs (kg/day)

| DATE | RUN# | PORT/ STAR-BOARD | METAL (kg/day) | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Fe | Cu | Ni | Pb | Zn | Cr | Cd | Mn | Co | Se | As | $SO_4$ | $N\text{-}NH_4$ |
| 2/1/80 | 2 | P | 698.5 | 48.8 | 75.4 | 19.7 | 14.0 | - | - | - | - | - | 3.6 | 5769.3 | - |
| | 2 | S | 1075.5 | 43.8 | 87.0 | 12.9 | - | - | - | 4.8 | - | - | 3.9 | 5966.0 | - |
| 2/2/80 | 1 | P | 576.8 | 130.3 | 100.9 | 61.0 | - | - | 3.0 | - | - | - | 31.6 | 18816.6 | 86.8 |
| | 1 | S | 557.7 | 126.0 | 100.9 | 51.0 | - | - | - | - | - | 0.57 | 12.5 | 20783.8 | - |
| 2/3/80 | 1 | P | 743.6 | 130.3 | 182.2 | 36.2 | - | 50.4 | 5.9 | - | - | - | 17.9 | 18889.2 | - |
| | 2 | P | 757.8 | 447.3 | 1493.7 | 57.5 | - | 9.8 | - | - | 23.8 | 1.4 | 30.8 | 9110.3 | - |
| | 1 | S | 1263.1 | 177.3 | 206.4 | 79.7 | - | - | 3.8 | - | - | 9.2 | 18.3 | 19872.3 | - |
| | 2 | S | 869.6 | 451.7 | 1342.0 | 59.9 | - | - | - | - | 27.0 | 4.4 | 22.7 | 9127.6 | - |
| 2/3/80 | 1 | P | 660.4 | 48.1 | 87.6 | 24.4 | 31.2 | - | 2.1 | - | - | - | 3.9 | 5718.2 | - |
| | 1 | S | 494.5 | 37.9 | 63.2 | 9.4 | - | - | - | - | - | - | 3.1 | 5523.6 | - |

Table 11: Summary of Estimated INCO IORP Stack Emission Rates for Individual Processes*+

| rameter | % Difference From Check** | Emission Rate (kg/min) IORP & CIL | CCNR CHARGE | CCNR BLOW | CCNR REDUCTION |
|---|---|---|---|---|---|
| $SO_4^=$ | -30% | 3.6 (1.00) | 2.9 (0.80) | 9.9 (2.77) | 1.0 (0.27) |
| Fe | +95% | 0.3 (1.00) | 0.2 (0.68) | 0.3 (1.00) | 0.3 (1.00) |
| Cu | -10% | 0.03 (1.00) | 0.3 (11.00) | 0.08 (2.67) | 0.01 (0.33) |
| Ni | +49% | 0.05 (1.00) | 1.2 (24.44) | 0.09 (1.77) | 0.02 (0.31) |
| As | -45% | 0.002 (1.00) | 0.02 (8.22) | 0.01 (4.57) | 0.0006 (0.26) |
| Pb | -18% | 0.01 (1.00) | 0.03 (3.15) | 0.04 (3.41) | 0.002 (0.18) |
| $SO_2$ | - | 95.8 | 5.7 | 143.0 | 31.0 |

* Numbers in brackets represent ratio of individual phase emission rate to emission rate from IORP & CIL.

\+ The estimated emission rates apply for average feedrate conditions during the study.

** See Appendix 1 for details.

**Table 12: Estimated Average Emission Rates from INCO IORP Stack (kg/day)**

| Parameter | Emission Rate (kg/day) IORP + CIL | CCNR | TOTAL |
|---|---|---|---|
| $SO_4^=$ | 5155.2 | 4064.4 | 9219.6 |
| Fe | 489.6 | 297.0 | 786.6 |
| Cu | 43.2 | 144.0 | 187.2 |
| Ni | 69.1 | 450.6 | 519.7 |
| As | 2.9 | 10.0 | 12.9 |
| Pb | 15.8 | 22.9 | 38.7 |
| $SO_2$ | $1.38 \times 10^5$ | $5.18 \times 10^4$ | $1.90 \times 10^5$ |

Table 13: Comparison of Airborne and In-Stack Measured Emission Rates (kg/day) of the INCO 381 m Chimney (1980)

| | Fe | Cu | Ni | Pb | Zn | Cr | Cd | Mn | Co | As | Mg | $SO_4$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| February 5* | | | | | | | | | | | | |
| Airborne | 1313.1 ±417.6+ | 403.3 ±98.1 | 580.1 ±221.0 | 406.4 ±114.7 | 35.7 ±5.9 | 4.8 - | 20.6 ±0.85 | 4.4 ±.99 | 19.9 ±2.3 | 127.8 ±20.7 | 69.9 ±31.0 | 32378.5 ±1185.1 |
| In-Stack | 6091.2 ±4215.5+ | 1097.3 ±782.0 | 2021.8 ±1612.9 | 600.5 ±213.8 | 105.0 ±34.8 | 94.6 ±25.1 | 62.2 ±22.0 | 22.0 ±14.1 | 69.6 ±53.2 | 108.4 ±23.8 | 239.8 ±143.6 | 23155 ±4765.3 |
| Ratio (A/I) | 0.22 | 0.37 | 0.29 | 0.68 | 0.34 | 0.05 | 0.33 | 0.20 | 0.29 | 1.18 | 0.29 | 1.40 |
| February 7 | | | | | | | | | | | | |
| Airborne | 483.6 ±78.4 | 308.0 ±21.3 | 184.0 ±22.1 | 339.0 ±57.0 | 49.0 ±15.2 | - | 19.1 ±4.5 | - | - | 157.3 ±38.7 | 73.1 - | 40189 ±9934.8 |
| In-Stack | 1991.5 ±262.7 | 632.5 ±40.3 | 555.6 ±83.1 | 528.3 ±20.2 | 87.3 ±15.9 | - | 30.02 ±.43 | - | - | 171.5 ±25.1 | 78.62 ±0.99 | 19483.2 ±2382.7 |
| Ratio (A/I) | 0.24 | 0.49 | 0.33 | 0.64 | 0.56 | - | 0.64 | - | - | 0.92 | 0.93 | 2.06 |

* Emissions atypical; particle falloff observed from the stack.
+ One standard deviation.

Table A1: Flow Volumes (litre) for Individual INCO 381 m Chimney Plume Flights

| Date | Run # | Andersen Sticky | Andersen Non-Sticky | 47 mm Port | 47 mm Starboard |
|---|---|---|---|---|---|
| Sept. 8/79 | 1 | 562 | 575 | 230 | 261 |
| | 2 | 876 | 892 | 385 | 369 |
| | 3 | 1172 | 1215 | 443 | 543 |
| | TOTAL | 2610 | 2682 | 1058 | 1173 |
| Jan. 31/80 | 1 | 1498 | 1566 | 639 | 690 |
| | 2 | 782 | 818 | 354 | 336 |
| | TOTAL | 2280 | 2384 | 993 | 1026 |
| Feb. 4/80 | 1 | 1696 | 1622 | 704 | 747 |
| | 2 | 1561 | 1496 | 650 | 731 |
| | TOTAL | 3257 | 3118 | 1354 | 1478 |
| Feb. 5/80 | 1 | 1325 | 1364 | 599 | 564 |
| | 2 | 1247 | 1303 | 506 | 615 |
| | TOTAL | 2572 | 2667 | 1105 | 1179 |
| Feb. 7/80 | 1 | 1506 | 1483 | 649 | 638 |
| | 2 | 1513 | 1447 | 584 | 639 |
| | TOTAL | 3019 | 2930 | 1233 | 1277 |

## Table A2: Flow Volumes (litre) for Individual INCO IORP Plume Flights

| Date | Run # | Andersen Sticky | Andersen Non-Sticky | 47 mm Port | 47 mm Starboard |
|---|---|---|---|---|---|
| Feb. 1/80 | 2 | 686 | 666 | 314 | 307 |
| | TOTAL | 686 | 666 | 314 | 307 |
| Feb. 2/80 | 1 | 414 | 420 | 203** | 184** |
| | 2 | 800 | 811 | 381** | 348** |
| | | | | 584 | 532 |
| (Feb. 3/80) | 1 | blocked off | blocked off | 239* | 228* |
| | 2 | 935 | 964 | 411 | 393 |
| | TOTAL | 2151 | 2195 | 995 | 925 |
| Feb. 8/80 | 1 | 132 | 128 | 61 | 57 |
| | TOTAL | 132 | 128 | 61 | 57 |

* not added to the total
** can be taken as one run (take the sum)

Table A3: Estimated $SO_2$ Emission Rates of INCO 381 m Chimney

| Date | Run # | Time at Sampling | $SO_2$ Emission Rate (MT/DAY) | Time-Weighted Average $SO_2$ Emission Rate (MT/DAY) |
|---|---|---|---|---|
| Sept. 8/79 | 1 | 0938 - 1014 hr | 1758 | |
| | 2 | 1250 - 1358 hr | 1677 | 1621+ |
| | 3 | 1512 - 1626 hr | 1383 | |
| Jan. 31/80 | 1 | 1155 - 1306 hr | 1720 | |
| | 2 | 1407 - 1444 hr | 1916 | |
| Feb. 4/80 | 1 | 1150 - 1301 hr | 2304 | 1955 |
| | 2 | 1433 - 1542 hr | 1716 | |
| Feb. 7/80 | 1 | 0949 - 1051 hr | 1945 | |
| | 2 | 1140 - 1245 hr | 2114 | |
| Feb. 5/80 | 1 | 1023 - 1129 hr* | 1089 | 1242** |
| | 2 | 1219 - 1321 hr | 1568 | |

* In-Stack $SO_2$ measurements were missing for part of this period. The estimated emission rate could be low by as much as 25%.

** Particle fallout observed during the study period. Run 1 is weighted twice for port and starboard for use in Table 7 calculations.

+ Runs 1 and 2 are weighted twice for port and starboard for use in Table 7 calculations.

Table A4: Summary of INCO IORP Stack Emission Sources During Sampling

| Date | Run | Time of Sampling | OPERATING CONDITIONS | | | | $SO_2$ Emission Rate(MT/Day) |
|---|---|---|---|---|---|---|---|
| | | | IORP + CIL | CCNR CHARGE | CCNR BLOW | CCNR REDUCTION | |
| 1 Feb. /80 | 1 | 1041 to 1121 | Continuous | - | - | Converter 2 1041 - 1121 | 163.9* |
| 2 Feb. /80 | 1 | 0934 to 1000 combined with 1032 to 1124 | Continuous | - | Converter 2 0934 - 0945 | - | 285.1 |
| | | | Continuous | - | Converter 1 1032 - 1110 | Converter 2 1032 - 1124 | |
| 3 Feb. /80 | 1 | 0843 to 0918 | Continuous | - | Converter 2 0845 - 0918 | - | 351.1 |
| | 2 | 1447 to 1541 | Continuous | Converter 2 1447 - 1541 | - | - | 173.2 |
| 8 Feb. /80 | 1 | 0806 to 0817 | Continuous | - | - | - | 147.9 |

* On February 1, 1980, some of the $SO_2$ emissions from IORP were directed at the IORP stack directly rather than through CIL as opposite to the other days.

Table A5: Summary of (M/Vol) Ratios in BNCO 381 m Chimney Plume Using 47 mm Packs*

| DATE | RUN# | PORT/ STAR-BOARD | PARAMETER (M) (ng/L) Fe | Cu | Ni | Pb | Zn | Cr | Cd | Mn | Co | Se | As | Mg | Si | $SO_4$ (ug/l) | $SO_2$ (ug/l) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Sept. 8 1979 | 1 | P | - | 4.35 | 0.87 | 3.48 | 0.87 | - | 7.83 | - | - | 0.22 | 0.65 | - | - | 0.28 | 15.87 |
| | 2 | P | 6.49 | 5.97 | 1.82 | 3.12 | 1.04 | - | 0.26 | 0.26 | - | 0.13 | 1.30 | - | - | 0.30 | 29.62 |
| | 3 | P | 8.35 | 10.84 | 1.35 | 1.58 | 0.90 | - | 0.23 | - | - | 0.18 | 0.90 | - | - | 0.23 | 11.26 |
| | 1 | S | 5.36 | 3.49 | 0.77 | 2.68 | 0.38 | - | 0.19 | - | - | 0.19 | 1.15 | - | - | 0.24 | 14.01 |
| | 2 | S | 6.78 | 4.88 | 1.63 | 3.52 | 1.08 | - | 0.14 | - | - | 0.22 | 1.49 | - | - | 0.30 | 29.80 |
| | 3 | S* | | | | | | | | | | | | | 25.8 | | 13.16 |
| Jan. 31 1980 | 1 | P | 12.35 | 4.59 | 3.88 | 5.98 | 0.91 | - | 0.25 | - | - | 0.49 | 2.83 | - | | 0.41 | 26.41 |
| | 2 | P | 11.22 | 4.10 | 4.61 | 6.07 | 0.88 | - | 0.44 | - | - | 1.05 | 3.19 | - | | 0.35 | 22.35 |
| | 1 | S | 9.86 | 4.64 | 3.55 | 6.20 | 1.15 | - | 0.29 | - | - | 0.29 | 2.41 | - | | 0.41 | 26.95 |
| | 2 | S | 20.00 | 6.19 | 6.91 | 7.56 | 0.92 | - | 0.34 | - | - | 0.98 | 3.36 | - | | 0.41 | 31.77 |
| Feb. 4 1980 | 1 | P | 29.86 | 8.67 | 10.41 | 12.67 | 1.61 | - | 0.58 | - | 0.25 | 0.14 | 2.61 | 1.12 | | 0.79 | 54.01 |
| | 2 | P | 11.12 | 3.59 | 3.74 | 5.57 | 0.35 | 0.13 | 0.40 | - | - | 0.16 | 1.29 | - | | 0.45 | 28.72 |
| | 1 | S | 18.96 | 6.88 | 7.58 | 18.16 | 1.55 | - | 0.57 | - | - | 0.16 | 2.46 | 0.81 | | 0.72 | 53.21 |
| | 2 | S | 10.36 | 3.67 | 3.63 | 5.16 | 0.36 | - | 0.31 | - | - | 0.16 | 0.97 | - | | 0.38 | 28.30 |
| Feb. 5 1980 | 1 | P | 50.25 | 15.91 | 29.04 | 12.27 | 1.05 | 0.16 | 0.66 | 0.17 | 0.71 | 4.59 | 4.79 | 3.07 | | 1.09 | 35.96 |
| | 2 | P | 31.42 | 11.07 | 12.31 | 20.16 | 1.60 | - | 0.81 | - | - | 4.98 | 3.95 | 1.30 | | 1.26 | 39.13 |
| | 1 | S | 52.48 | 14.42 | 22.70 | 10.37 | 1.08 | - | 0.67 | 0.13 | 0.60 | 5.92 | 4.42 | 2.71 | | 1.03 | 36.03 |
| | 2 | S | 31.87 | 11.43 | 13.63 | 12.81 | 1.15 | - | 0.69 | - | 0.28 | 4.94 | 3.13 | 1.66 | | 0.82 | 6.65 |
| Feb. 7 1980 | 1 | P | 11.56 | 8.37 | 5.05 | 10.31 | 1.56 | - | 0.65 | - | - | 1.27 | 3.74 | - | | 1.19 | 49.05 |
| | 2 | P | 13.77 | 8.31 | 5.45 | 9.42 | 1.08 | - | 0.67 | - | - | 2.86 | 4.49 | - | | 1.10 | 55.97 |
| | 1 | S | 10.46 | 7.38 | 4.08 | 9.25 | 1.58 | - | 0.47 | - | - | 1.76 | 3.19 | - | | 1.19 | 49.96 |
| | 2 | S | 12.68 | 7.67 | 4.66 | 6.96 | 0.86 | - | 0.41 | - | - | 2.58 | 2.99 | 1.99 | | 0.70 | 57.52 |

* Only samples with loadings equal to or greater than 2x filter blank were included in calculations.
* Filter used entirely for Si analysis by DC arc.

Table A6- Page 1: Summary of M/$SO_4$ Ratios in INCO 381 in Chimney Plume Using 47 mm Filter Packs*

| DATE | RUN# | PORT/ STAR-BOARD | PARAMETER (M) Fe $x10^{-4}$ | Cu $x10^{-4}$ | Ni $x10^{-4}$ | Pb $x10^{-4}$ | Zn $x10^{-5}$ | Cr $10^{-6}$ | Cd $10^{-6}$ | Mn $x10^{-6}$ | Co $x10^{-6}$ | Se $x10^{-5}$ | As $x10^{-4}$ | Mg $x10^{-5}$ | $SO_4$ $x10^{-2}$ | Si $x10^{-5}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1979 | | | | | | | | | | | | | | | | |
| Sept. 8 | 1 | P | - | 2.74 | .548 | 2.19 | 5.48 | - | 493** | - | - | 1.37 | .411 | - | 1.78 | - |
| | 2 | P | 2.64 | 2.43 | .739 | 1.27 | 9.22 | - | 10.6 | 10.6 | - | 5.28 | .0528 | - | 1.20 | - |
| | 3 | P | 7.43 | 9.64 | 1.20 | 1.41 | 8.03 | - | 26.1 | - | - | 1.61 | .803 | - | 2.08 | - |
| | 1 | S | 3.83 | 2.49 | .547 | 1.91 | 2.74 | - | 13.7 | - | - | 1.37 | .821 | - | 1.71 | - |
| | 2 | S | 2.73 | 1.97 | .656 | 1.42 | 9.37 | - | 5.46 | - | - | .874 | .601 | - | 1.22 | - |
| | 3 | S | - | - | - | - | - | - | - | - | - | - | - | - | - | 1.96 |
| Average | | | 4.16 | 3.85 | .738 | 1.66 | 4.97 | - | 12.47 | 10.6 | - | 1.15 | .633 | - | 1.60 | 1.96 |
| Std. Dev. | | | 2.25 | 3.25 | .271 | 0.39 | 1.97 | - | 6.12 | - | - | 0.44 | .177 | - | 0.38 | - |
| 1980 | | | | | | | | | | | | | | | | |
| Jan. 31 | 1 | P | 4.73 | 1.74 | 1.47 | 2.26 | 3.44 | - | 9.42 | - | - | 1.84 | 1.07 | - | 1.56 | - |
| | 2 | P | 5.02 | 1.83 | 2.06 | 2.71 | 3.92 | - | 19.72 | - | - | 4.68 | 1.43 | - | 1.55 | - |
| | 1 | S | 3.66 | 1.72 | 1.32 | 2.30 | 4.25 | - | 10.70 | - | - | 1.08 | 0.89 | - | 1.53 | - |
| | 2 | S | 6.30 | 1.93 | 2.17 | 2.38 | 2.90 | - | 16.96 | - | - | 3.09 | 1.06 | - | 1.29 | - |
| Feb. 6 | 1 | P | 4.60 | 1.60 | 1.93 | 3.42 | 2.97 | - | 10.81 | - | 4.60 | 0.26 | 0.48 | 2.08 | 1.46 | - |
| | 2 | P | 5.87 | 1.25 | 1.30 | 1.90 | 1.23 | 4.34 | 13.93 | - | - | 0.34 | 0.65 | - | 1.58 | - |
| | 1 | S | 3.36 | 1.29 | 1.42 | 3.41 | 2.91 | - | 16.79 | - | - | 0.30 | 0.44 | 1.53 | 1.36 | - |
| | 2 | S | 5.66 | 1.30 | 1.28 | 1.82 | 1.26 | - | 10.88 | - | - | 0.58 | 0.34 | - | 1.33 | - |
| Feb. 7 | 1 | P | 2.96 | 1.71 | 1.03 | 1.98 | 3.17 | - | 9.08 | - | - | 3.99 | 0.76 | - | 2.43 | - |
| | 2 | P | 2.32 | 1.48 | 0.97 | 1.68 | 1.93 | - | 12.06 | - | - | 5.11 | 0.80 | - | 1.96 | - |
| | 1 | S | 2.13 | 1.57 | 0.82 | 1.85 | 3.17 | - | 9.44 | - | - | 3.51 | 1.04 | - | 2.38 | - |
| | 2 | S | 2.20 | 1.33 | 0.81 | 1.21 | 1.50 | - | 7.05 | - | - | 4.69 | 0.52 | 3.46 | 1.22 | - |
| Average | | | 3.74 | 1.67 | 1.38 | 2.25 | 2.72 | 4.34 | 11.74 | - | 4.60 | 2.46 | 0.78 | 2.36 | 1.64 | - |
| Std. Dev. | | | 1.27 | 0.21 | 0.46 | 0.67 | 1.01 | - | 3.56 | - | - | 1.88 | 0.33 | 0.99 | 0.41 | - |

* Only samples with loadings equal to or larger than 2x filter blank were included in calculations.
** Not included in calculations.

Table A6- Page 2: Summary of M/$SO_2$ Ratios in INCO 381 in Chimney Plume Using 47 mm Filter Packs*

| | | | PARAMETER (M) | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| DATE | RUN# | PORT/ STAR-BOARD | Fe $\times 10^{-4}$ | Cu $\times 10^{-4}$ | Ni $\times 10^{-4}$ | Pb $\times 10^{-4}$ | Zn $\times 10^{-3}$ | Cr $10^{-6}$ | Cd $10^{-6}$ | Mn $\times 10^{-4}$ | Co $\times 10^{-6}$ | Se $\times 10^{-5}$ | As $\times 10^{-4}$ | Mg $\times 10^{-3}$ | $SO_4$ $\times 10^{-2}$ | Sb $\times 10^{-3}$ |
| Feb. 3* | 1 | P | 13.97 | 4.42 | 6.69 | 3.41 | 2.93 | 4.36 | 18.38 | 4.64 | 19.73 | 12.77 | 1.33 | 8.54 | 3.02 | - |
| | 2 | P | 5.31 | 1.87 | 2.08 | 3.41 | 2.71 | - | 13.77 | - | - | 8.42 | 6.68 | 2.21 | 2.12 | - |
| | 1 | S | 14.57 | 4.60 | 6.30 | 2.88 | 3.00 | - | 18.65 | 3.69 | 16.73 | 16.04 | 1.23 | 7.53 | 2.85 | - |
| | 2** | S | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| Average | | | 11.28 | 3.63 | 5.02 | 3.23 | 2.88 | 4.36 | 16.93 | 4.17 | 18.23 | 12.54 | 1.08 | 6.09 | 2.66 | - |
| Std. Dev. | | | 5.18 | 1.37 | 2.56 | 0.31 | 0.15 | - | 2.74 | 0.67 | 2.12 | 4.01 | 0.36 | 3.40 | 0.48 | - |

* Emissions on this day were not representative of typical emissions.

** $SO_2$ value unusual (4690 ug)

* Only samples with loadings equal to or larger than 2x filter blank were included in calculations.

Table A7: Summary of (M/Vol) Ratios in INCO IOBP Stack PLUME Using 47 mm Filter Packs

| DATE | RUN# | PORT/ STAR-BOARD | PARAMETER (M) (ng/L) Fe | Cu | Ni | Pb | Zn | Cr | Cd | Mn | Co | Se | As | N-$NH_3$ | $SO_2$ (ug/l) | $SO_2$ (ug/l) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Feb. 1 1980 | 2 | P | 36.31 | 2.59 | 3.92 | 1.02 | 0.73 | - | - | - | - | - | 0.19 | - | 0.30 | 8.52 |
| | 2 | S | 30.40 | 2.22 | 4.40 | 0.65 | - | - | - | 0.24 | - | - | 0.20 | - | 0.30 | 8.29 |
| Feb. 2 1980 | 1 | P | 36.99 | 8.36 | 6.47 | 3.90 | - | - | 0.19 | - | - | - | 2.04 | 5.57 | 1.21 | 18.28 |
| | 1 | S | 36.84 | 8.33 | 6.67 | 3.37 | - | - | - | - | - | 0.04 | 0.83 | - | 1.37 | 18.84 |
| Feb. 3 1980 | 1 | P | 21.00 | 3.68 | 5.15 | 1.59 | - | 1.42 | 0.17 | - | - | - | 0.50 | | 0.53 | 9.92 |
| | 2 | P | 26.28 | 15.52 | 51.83 | 2.00 | - | 0.36 | - | - | 0.83 | 0.049 | 1.07 | - | 0.32 | 6.01 |
| | 1 | S | 36.27 | 5.09 | 5.92 | 2.28 | - | - | 0.11 | - | - | 0.26 | 0.53 | - | 0.57 | 10.07 |
| | 2 | S | 30.28 | 15.73 | 53.69 | 2.09 | - | - | - | - | 0.94 | 0.15 | 0.79 | - | 0.32 | 6.03 |
| Feb. 8 1980 | 1 | P | 142.13 | 10.33 | 18.85 | 5.25 | 6.72 | - | 0.84 | - | - | - | 0.82 | - | 1.23 | 32.21 |
| | 1 | S | 89.82 | 8.42 | 14.04 | 2.11 | - | - | - | - | - | - | 0.70 | - | 1.23 | 33.25 |

Table A8: Summary of $M/SO_2$ Ratios in the INCO IORP Stack Using 47 mm Filter Packs

| DATE | RUN# | PORT/ STAR-BOARD | PARAMETER (M) Fe $x10^{-4}$ | Cu $x10^{-4}$ | Ni $x10^{-4}$ | Pb $x10^{-4}$ | Zn $x10^{-5}$ | Cr $10^{-6}$ | Cd $10^{-6}$ | Mn $x10^{-6}$ | Co $x10^{-6}$ | Se $x10^{-5}$ | As $x10^{-4}$ | $SO_4$ $x10^{-2}$ | $N\text{-}NH_4$ $x10^{-3}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1980 | | | | | | | | | | | | | | | |
| Feb. 1 | 2 | P | 42.62 | 2.98 | 4.60 | 1.20 | 8.57 | - | - | - | - | - | 0.22 | 3.52 | - |
| | 2 | S | 65.62 | 2.67 | 5.31 | 0.79 | - | - | - | 29.47 | - | - | 0.24 | 3.64 | - |
| Feb. 2 | 1 | P | 26.23 | 4.57 | 3.54 | 2.14 | - | - | 10.40 | - | - | - | 1.11 | 6.60 | 30.45 |
| | 1 | S | 19.56 | 4.42 | 3.54 | 1.79 | - | - | - | - | - | 0.20 | 0.44 | 7.29 | - |
| Feb. 3 | 1 | P | 21.18 | 3.71 | 5.19 | 1.60 | - | 143.46 | 16.88 | - | - | - | 0.51 | 5.38 | - |
| | 2 | P | 43.73 | 25.83 | 86.24 | 3.32 | - | 56.68 | - | - | 137.65 | 0.81 | 1.78 | 5.26 | - |
| | 1 | S | 36.04 | 5.05 | 5.88 | 2.27 | - | - | 10.89 | - | - | 2.61 | 0.52 | 5.66 | - |
| | 2 | S | 50.21 | 26.08 | 89.03 | 3.46 | - | - | - | - | 156.12 | 2.53 | 1.31 | 5.27 | - |
| Feb. 8 | 1 | P | 44.12 | 3.21 | 5.85 | 1.63 | 20.87 | - | 13.74 | - | - | - | 0.26 | 3.82 | - |
| | 1 | S | 27.31 | 2.53 | 4.22 | 0.63 | - | - | - | - | - | - | 0.21 | 3.69 | - |
| Average | | | 37.63 | 8.11 | 21.34 | 1.88 | 14.72 | 100.07 | 12.98 | 29.47 | 146.89 | 1.54 | 0.66 | 5.01 | 30.45 |
| Std. dev. | | | 15.12 | 9.44 | 34.96 | 0.95 | 8.70 | 61.36 | 2.99 | - | 13.06 | 1.22 | 0.55 | 1.32 | - |

TABLE A9: Summary of Total (M/Vol) Ratios in INCO 381 m Chimney Plume Using Andersen Sampler

PARAMETER (M) - ng/l

| DATE | Sticky Substrate | | | | | | | | | | Non-Sticky Substrate | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Fe | Cu | Ni | Pb | Zn | Al | Cr | Cd | Mn | Mg | Se | As | $SO_4$ (ug/l) | N-$NH_4$ |
| 9/9/79 | 12.8 | 7.41 | 1.55 | 1.57 | 0.88 | 2.07 | - | 2.22 | 0.084 | - | - | - | 0.19 | 2.65 |
| 1/31/80 | 32.08 | 5.22 | 6.73 | 13.50 | 1.81 | 4.85 | 0.63 | 1.94 | - | 1.02 | - | 1.98 | 0.32 | 5.71 |
| 2/4/80 | 49.76 | 9.02 | 13.81 | 16.86 | 1.44 | 2.52 | 0.10 | 0.47 | - | 1.45 | - | 1.46 | 0.58 | 6.00 |
| 2/5/80 | 155.53 | 30.93 | 53.19 | 21.36 | 2.08 | 4.44 | - | 0.34 | - | 5.21 | 2.23 | 3.36 | 0.58 | 5.51 |
| 2/7/80 | 11.29 | 10.32 | 4.56 | 14.72 | 2.67 | 1.38 | - | 0.43 | - | 0.55 | 1.46 | 4.17 | 0.86 | 6.38 |

TABLE A10: Summary of Total (M/Vol) Ratios in INCO IORP Plume Using Andersen Sampling

| DATE | PARAMETER (M) - ng/l | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Sticky Substrate | | | | | | | | | | Non-Sticky Substrate | | |
| | Fe | Cu | Ni | Pb | Zn | Al | Cr | Cd | Co | Mg | As | $SO_4$ | $N\text{-}NH_4$ (ug/l) |
| 1980 | | | | | | | | | | | | | |
| Feb. 1 | 69.10 | 3.56 | 3.38 | 4.02 | 1.88 | 14.07 | 1.82 | 6.38 | - | 0.77 | - | 364.43 | 19.24 |
| Feb. 2-3 | 32.53 | 13.57 | 32.59 | 5.41 | - | - | - | 0.08 | 0.62 | 0.33 | 0.62 | 681.09 | 9.84 |
| Feb. 8 | 117.05 | 8.26 | 13.41 | - | - | 143.94 | - | 2.14 | - | - | - | 1074.22 | 78.91 |

## TABLE A11

Total Mass Emitted from IORP Stack During Airborne Sampling Periods

| Date | Paramter Emissions (kg) | | | | | |
|---|---|---|---|---|---|---|
| | $SO_4^=$ | Fe | Cu | Ni | Pb | As |
| Feb. 1/80 | 163 | 24.6 | 1.29 | 2.26 | 0.453 | 0.104 |
| Feb. 2/80 | 1073 | 30.7 | 6.94 | 5.47 | 3.033 | 1.194 |
| Feb. 3/80(run 1) | 471 | 24.4 | 3.74 | 4.72 | 1.652 | 0.440 |
| Feb. 3/80(run 2) | 342 | 30.5 | 16.86 | 56.92 | 2.201 | 1.003 |
| Feb. 7/80 | 43 | 4.1 | 0.33 | 0.58 | 0.129 | 0.027 |

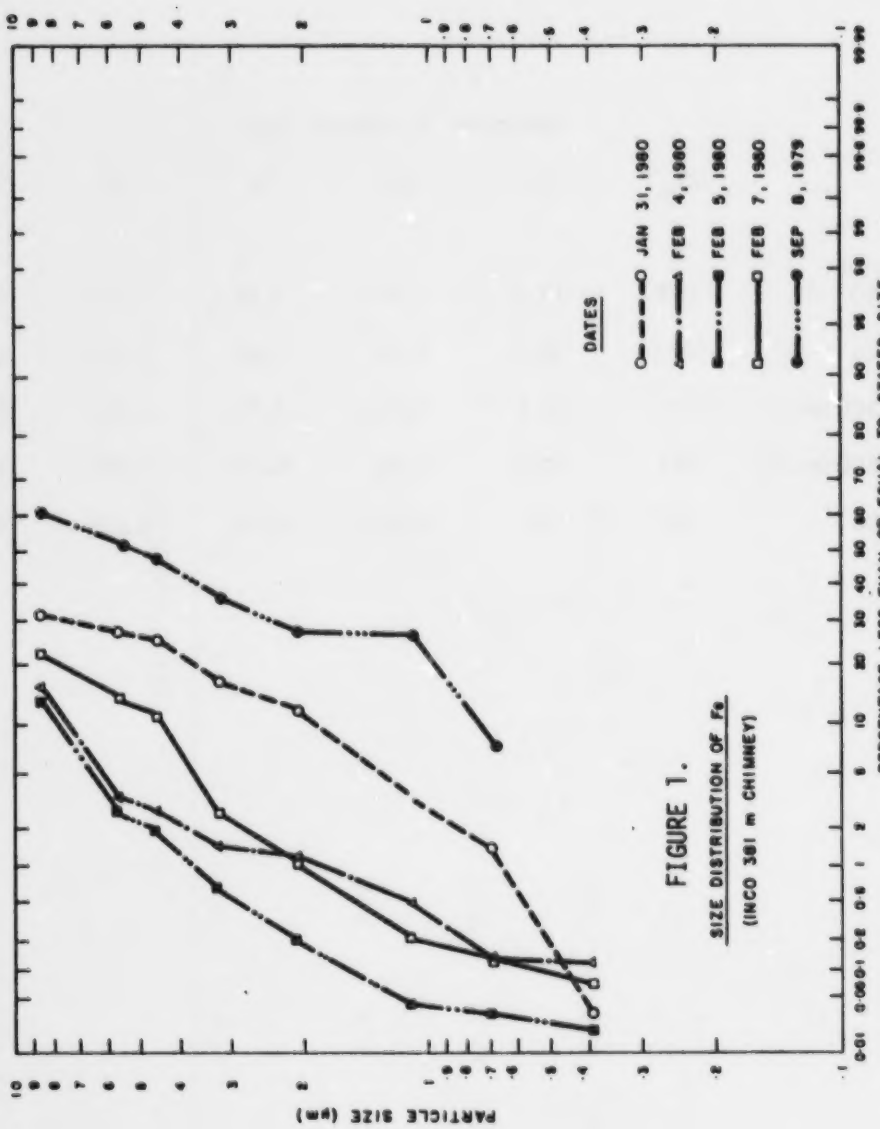



FIGURE 1.

SIZE DISTRIBUTION OF Fe

(INCO 381 m CHIMNEY)

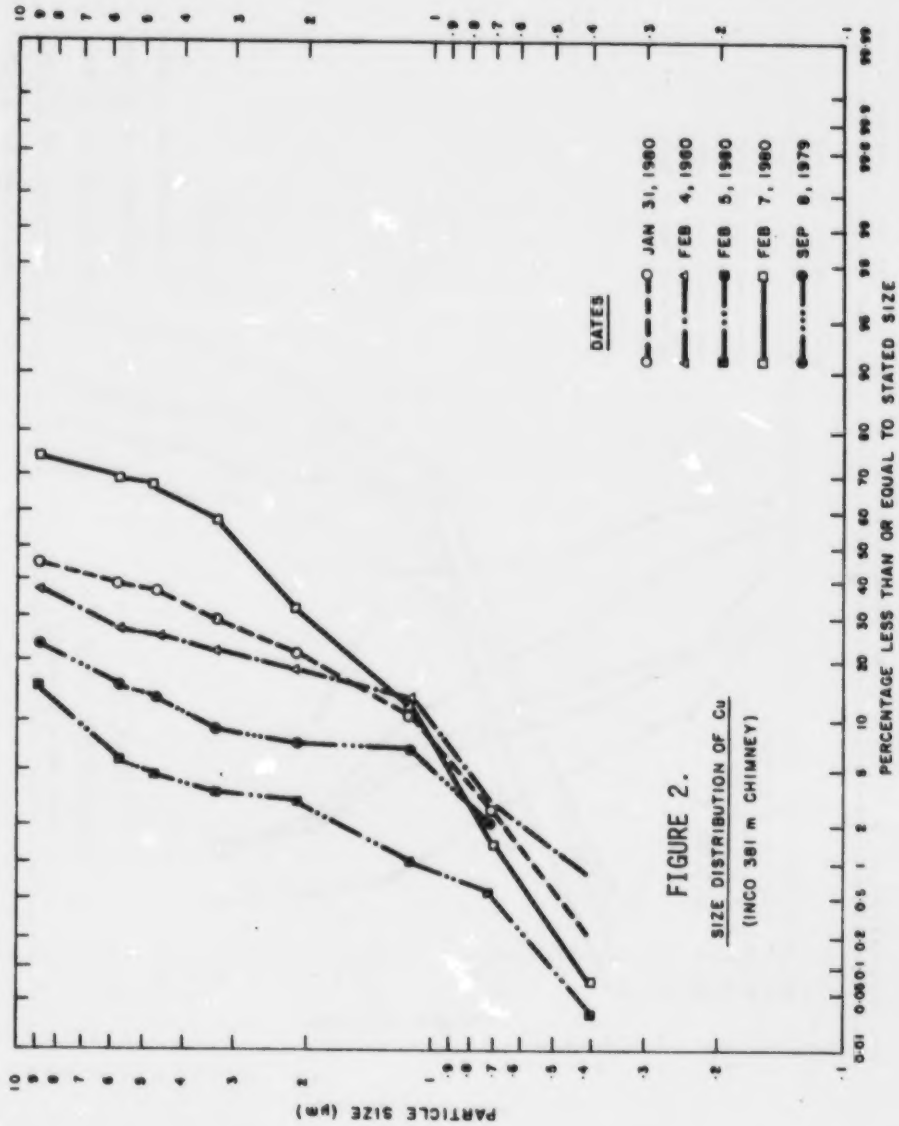



FIGURE 2.

SIZE DISTRIBUTION OF Cu

(INCO 381 m CHIMNEY)

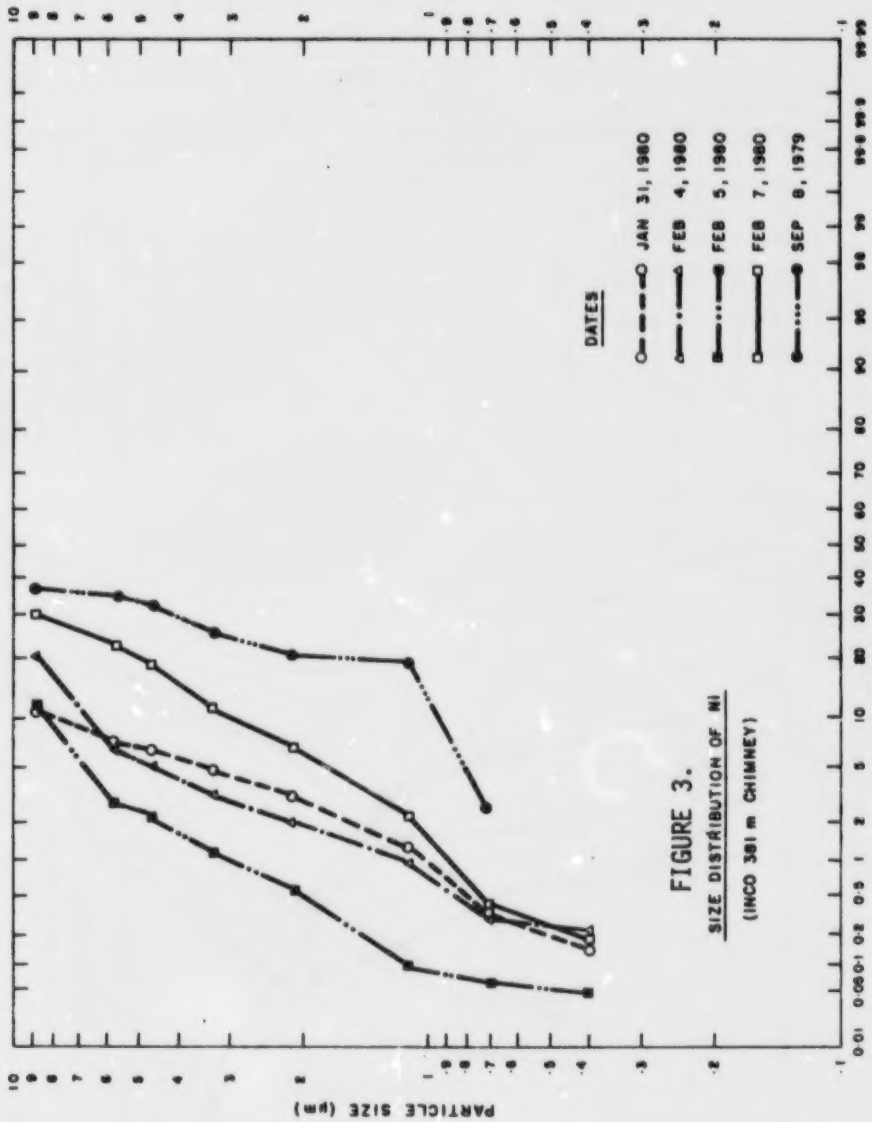

PARTICLE SIZE (μm)
PERCENTAGE LESS THAN OR EQUAL TO STATED SIZE
DATES
JAN 31, 1980
FEB 4, 1980
FEB 5, 1980
FEB 7, 1980
SEP 8, 1979
SIZE DISTRIBUTION OF Ni
(INCO 381 m CHIMNEY)

FIGURE 3.

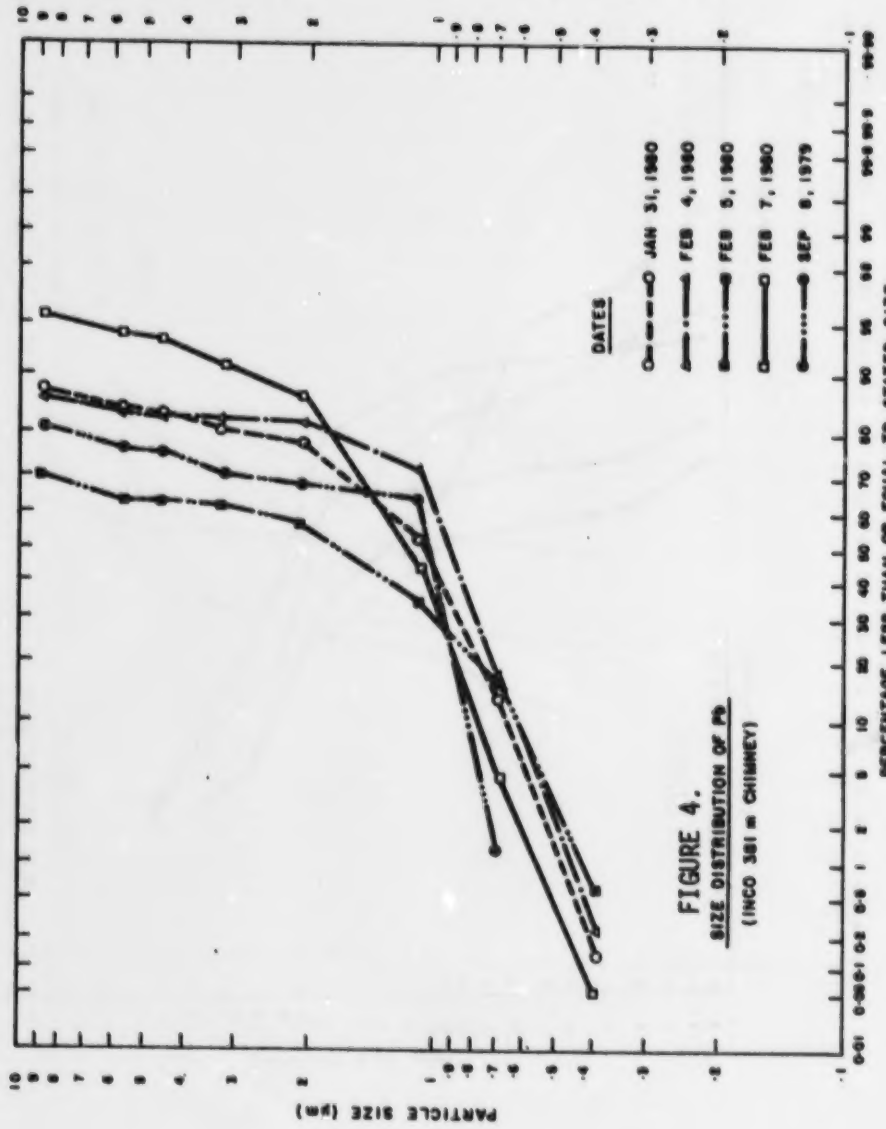



FIGURE 4.
SIZE DISTRIBUTION OF Pb
(INCO 381 m CHIMNEY)

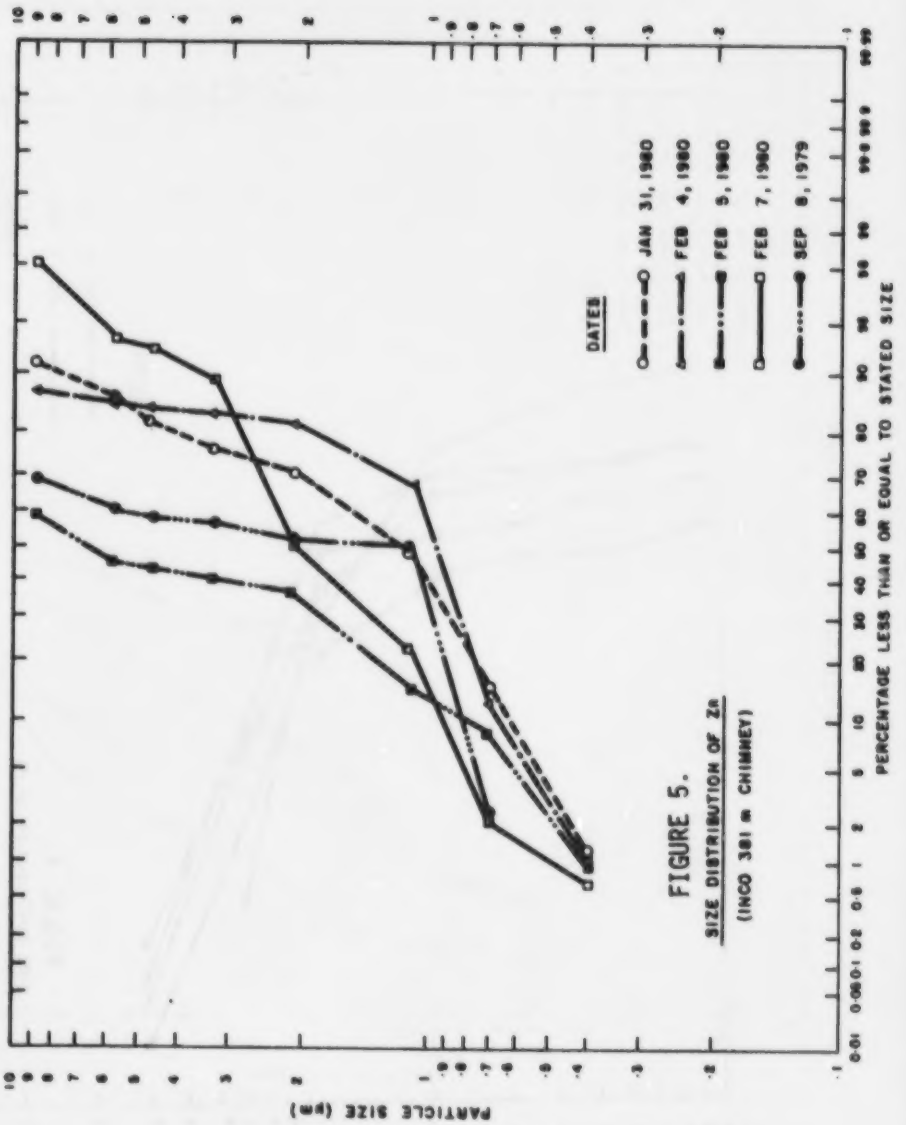



FIGURE 5.
SIZE DISTRIBUTION OF Zn
(INCO 381 m CHIMNEY)

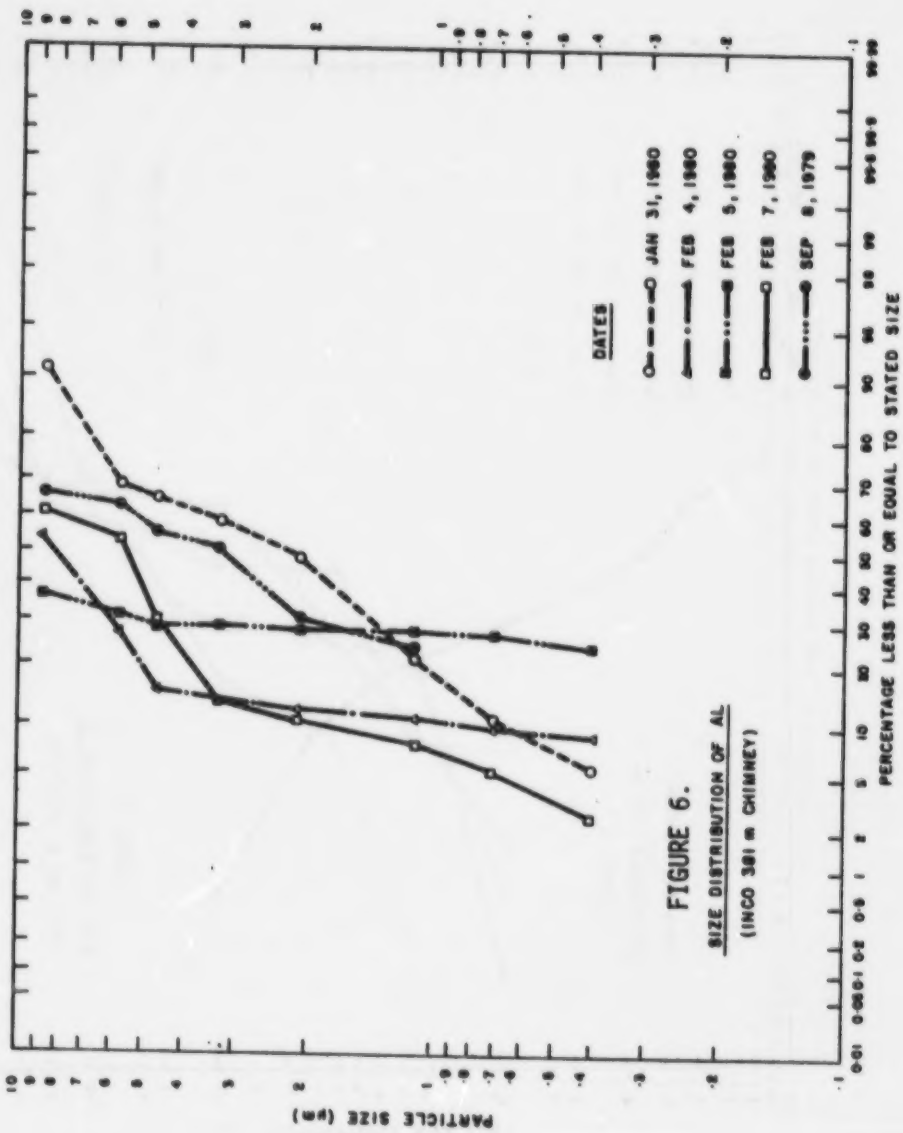



FIGURE 6.

SIZE DISTRIBUTION OF AL

(INCO 381 m CHIMNEY)

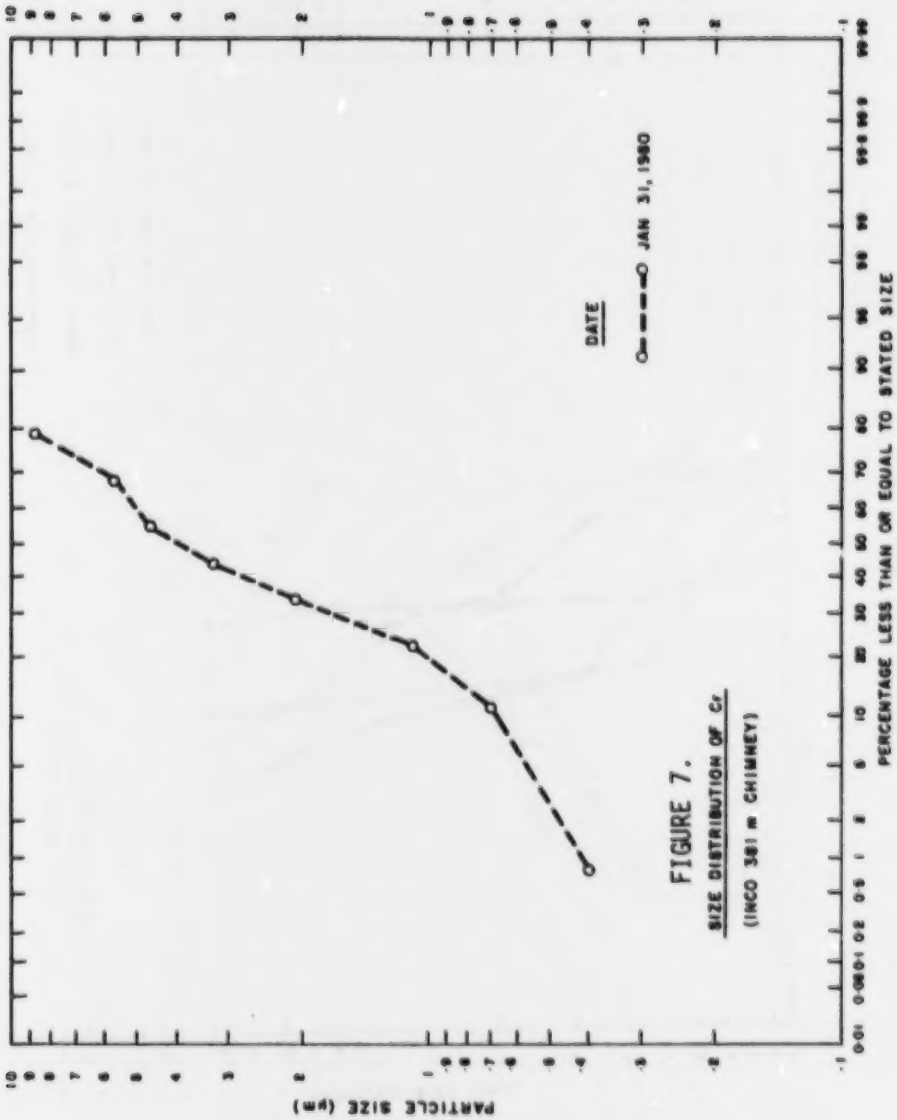



FIGURE 7.
SIZE DISTRIBUTION OF Cr
(INCO 381 m CHIMNEY)

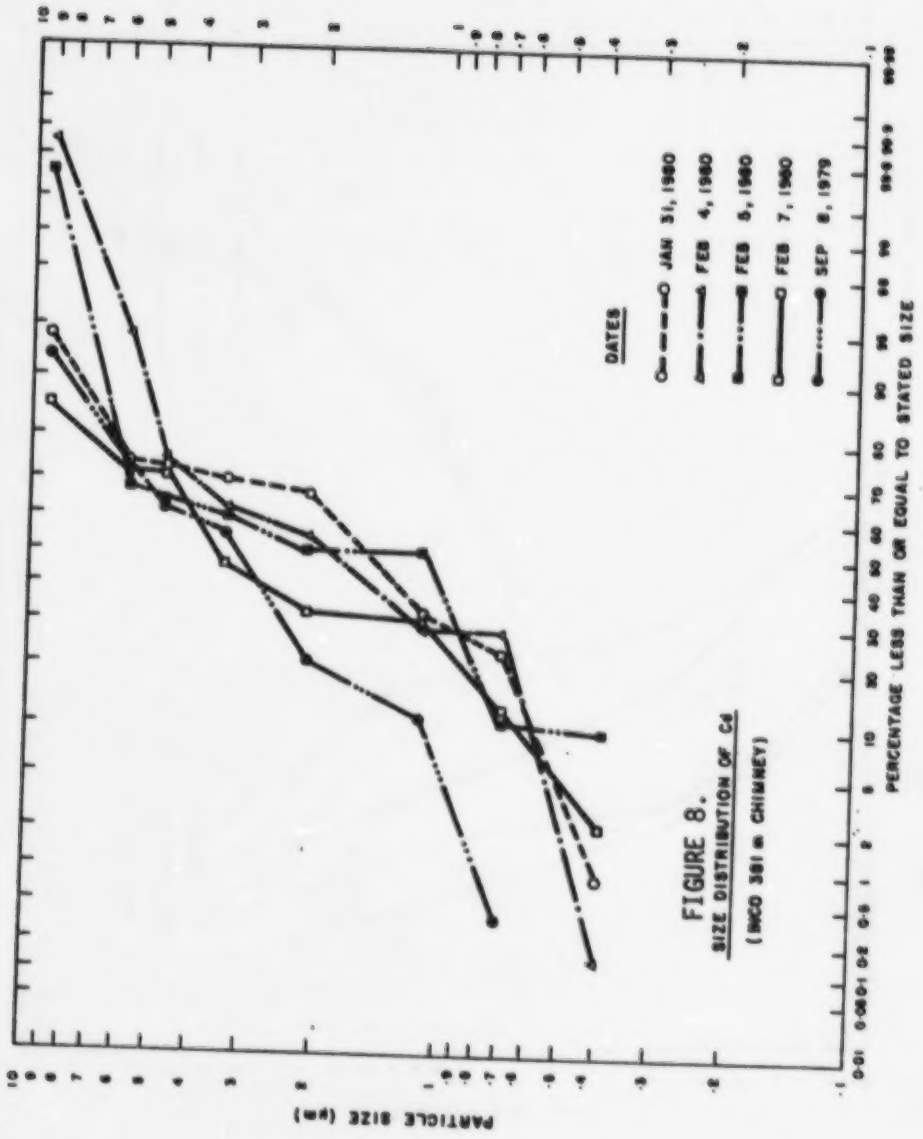



FIGURE 8.
SIZE DISTRIBUTION OF Cd
(INCO 381 m CHIMNEY)

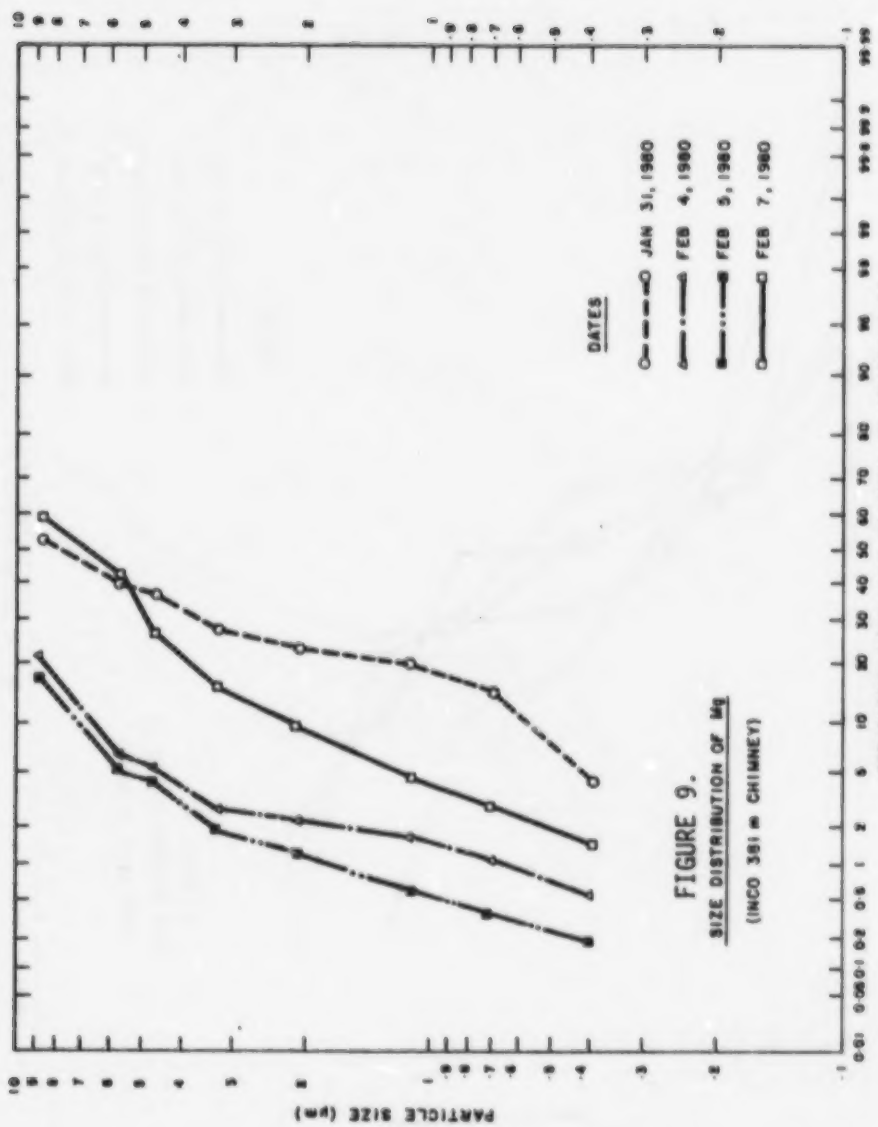



FIGURE 9.
SIZE DISTRIBUTION OF Hg
(INCO 381 m CHIMNEY)

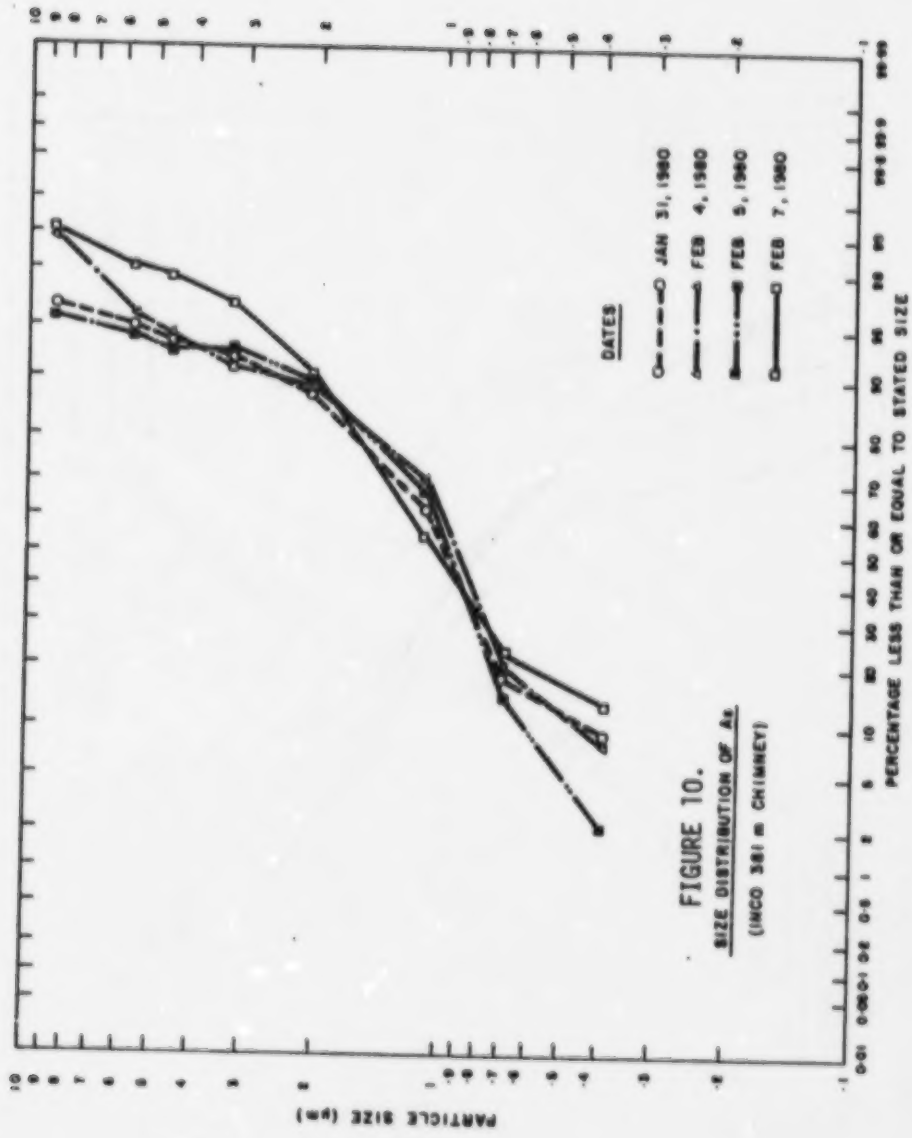



FIGURE 10.
SIZE DISTRIBUTION OF As
(INCO 381 m CHIMNEY)

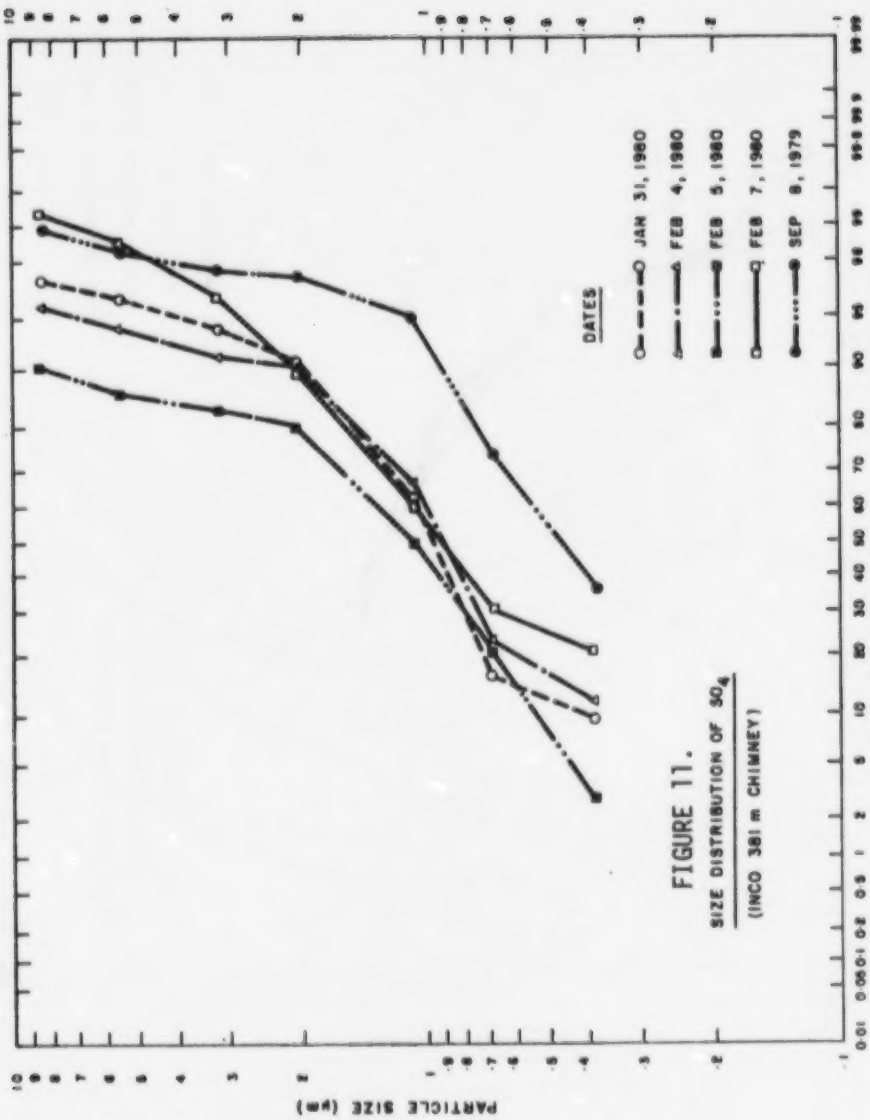



FIGURE 11.
SIZE DISTRIBUTION OF $SO_4$
(INCO 381 m CHIMNEY)

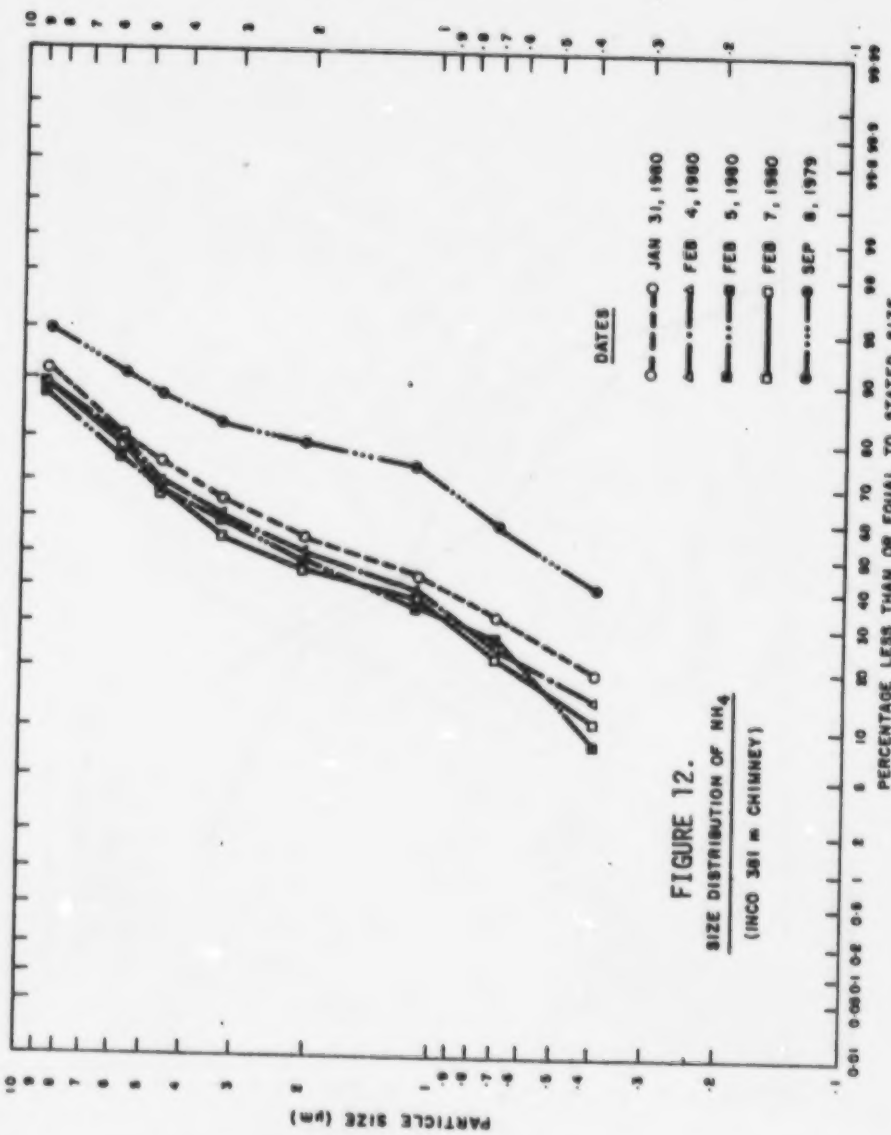



FIGURE 12.
SIZE DISTRIBUTION OF $NH_4$
(INCO 381 m CHIMNEY)

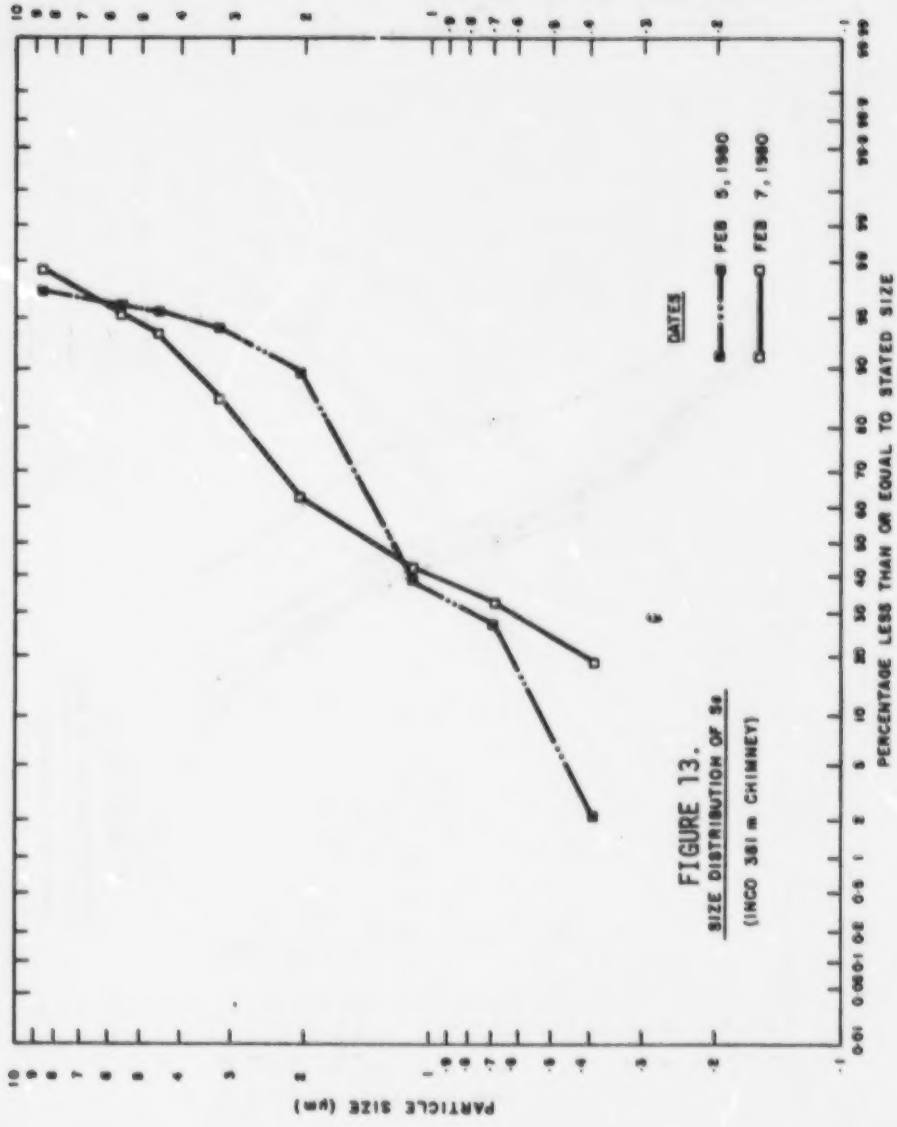



FIGURE 13.
SIZE DISTRIBUTION OF Se
(INCO 381 m CHIMNEY)

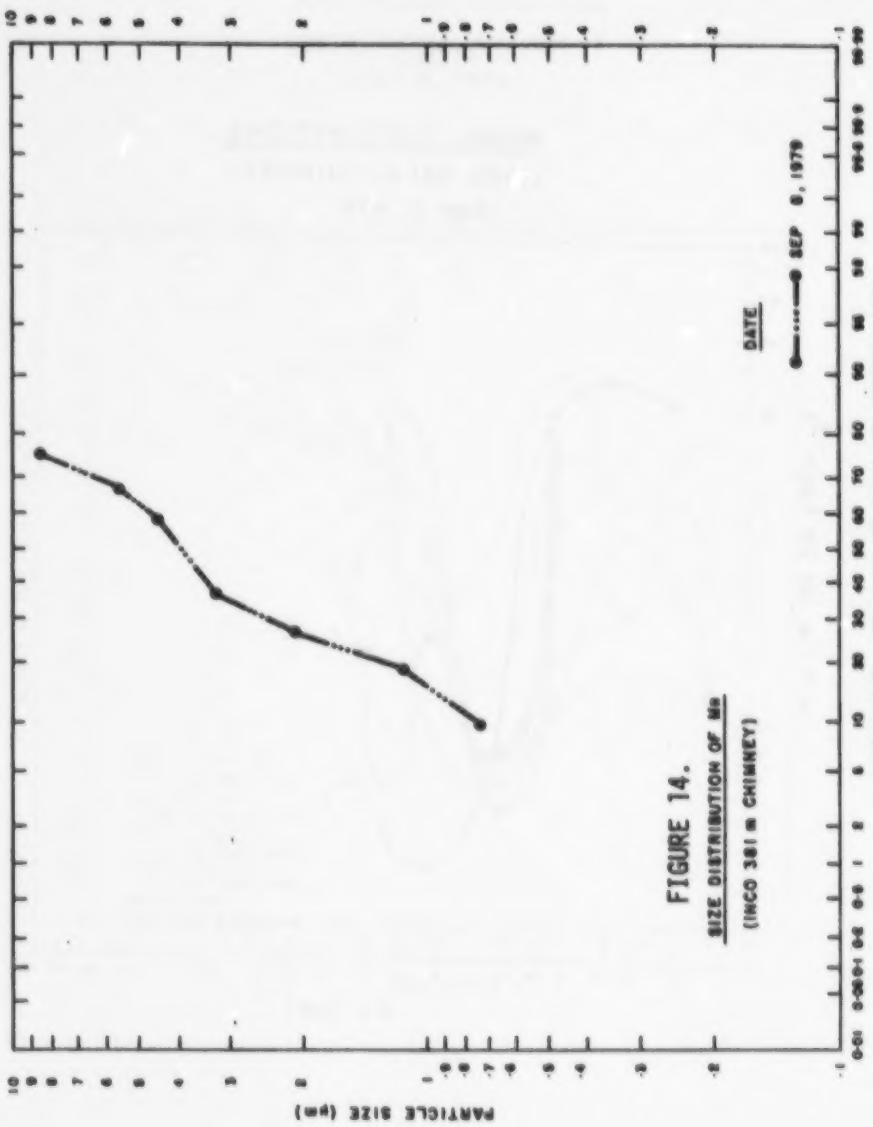



FIGURE 14.
SIZE DISTRIBUTION OF Nb
(INCO 381 m CHIMNEY)

FIGURE 15

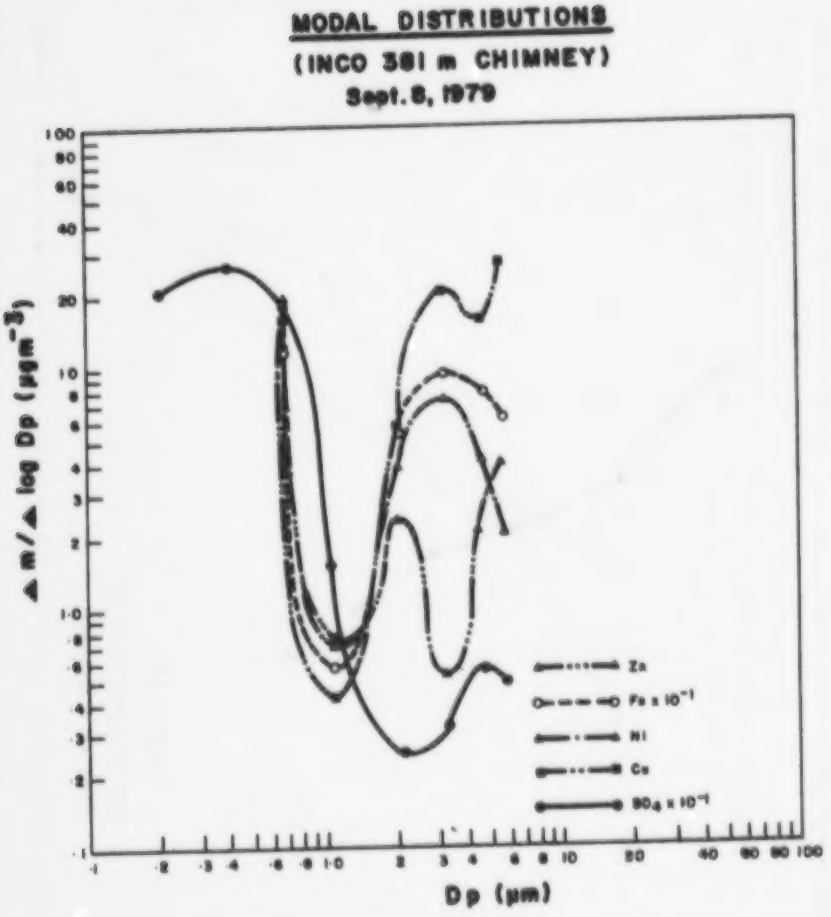

MODAL DISTRIBUTIONS
(INCO 381 m CHIMNEY)
Sept. 8, 1979
Δ m/Δ log Dp (μgm⁻³)
Dp (μm)
Zn
Fe x 10⁻¹
Ni
Cu
SO4 x 10⁻¹

FIGURE 16

**MODAL DISTRIBUTIONS**

**(INCO 381 m CHIMNEY)**

**Sept. 8, 1979**

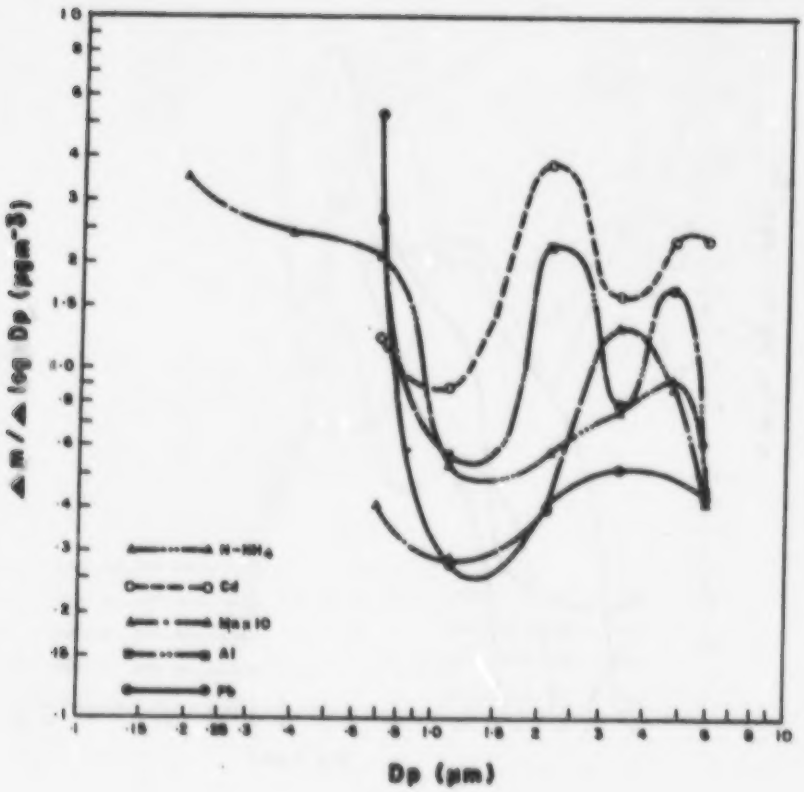


FIGURE 17

**MODAL DISTRIBUTION OF Fe**

**(INCO 381 m CHIMNEY)**

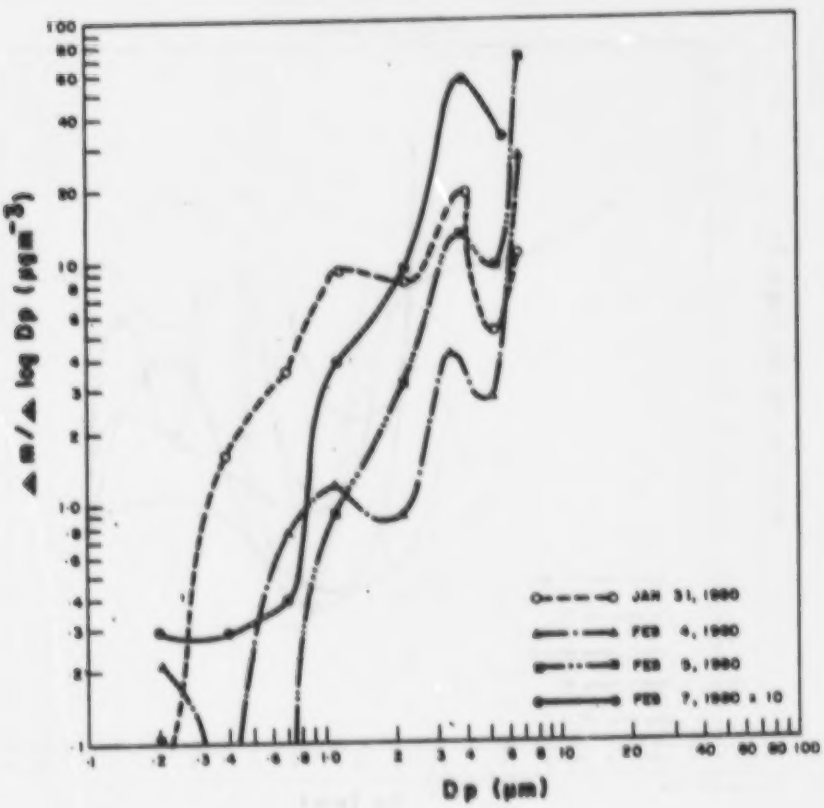


FIGURE 18

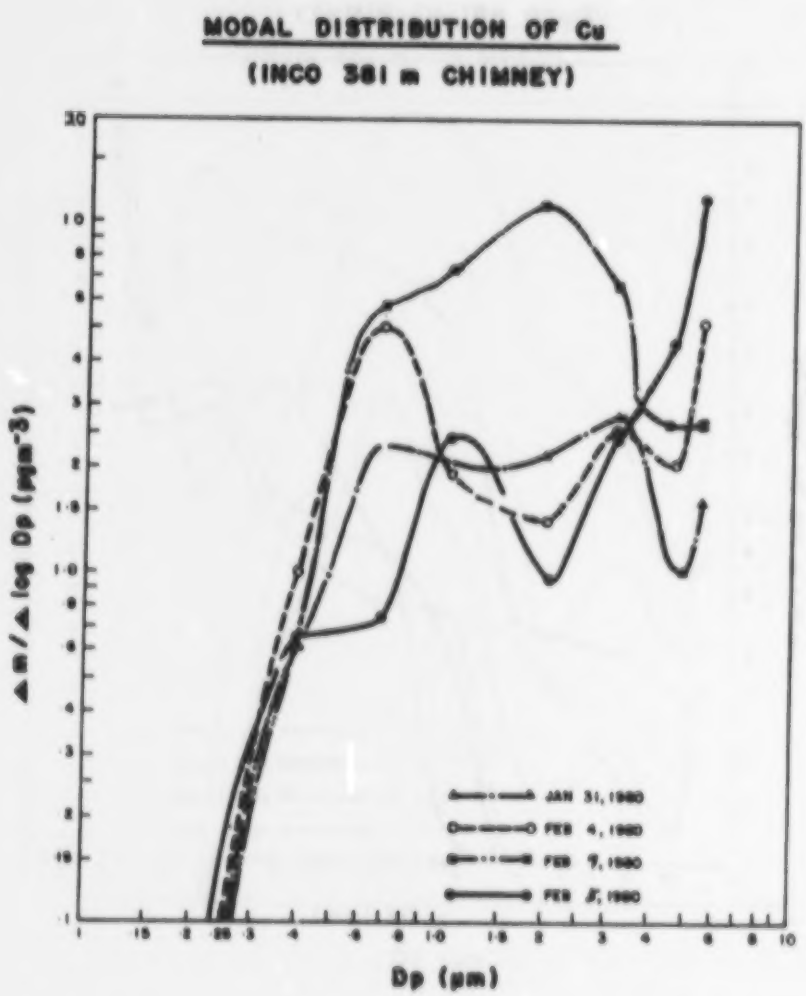

MODAL DISTRIBUTION OF Cu
(INCO 381 m CHIMNEY)
Δm/Δ log Dp (μgm⁻³)
Dp (μm)
JAN 31, 1980
FEB 4, 1980
FEB 9, 1980
FEB 11, 1980

FIGURE 19

MODAL DISTRIBUTION OF NI

(INCO 381 m CHIMNEY)

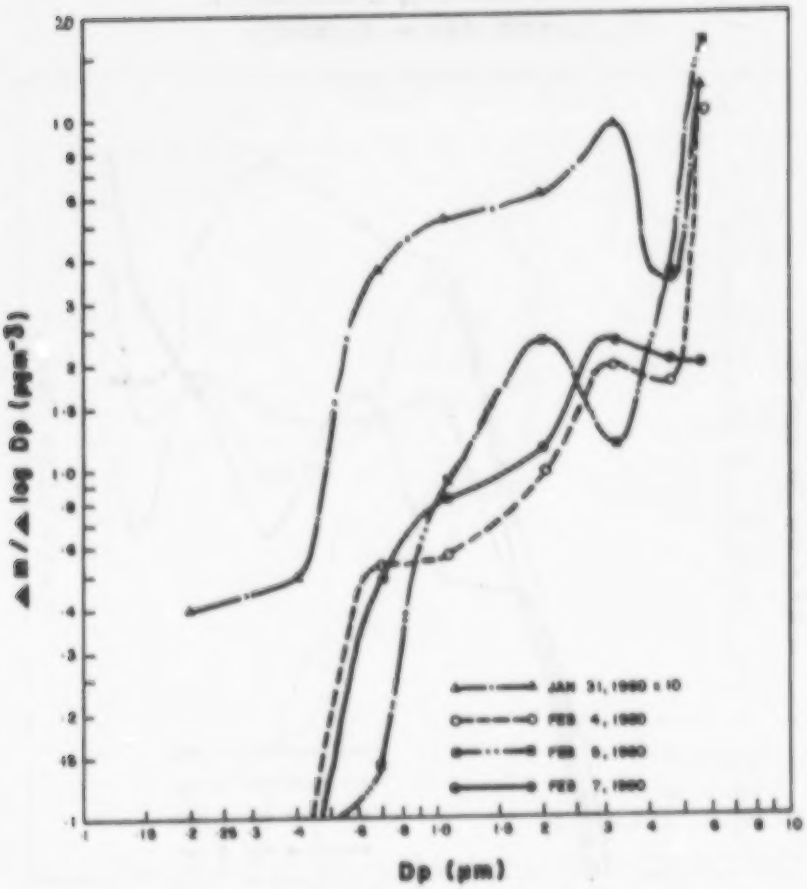


FIGURE 20

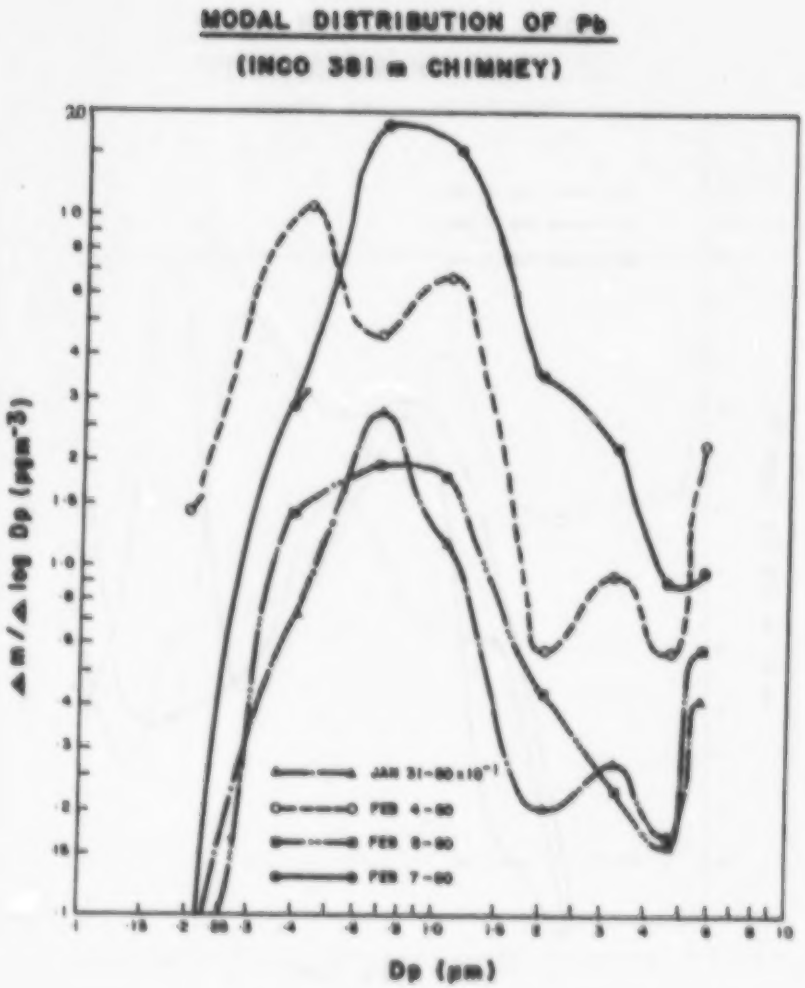

MODAL DISTRIBUTION OF Pb
(INCO 381 m CHIMNEY)
Δm/Δ log Dp (μgm⁻³)
Dp (μm)
JAN 31-80 x 10⁻¹
FEB 4-80
FEB 5-80
FEB 7-80

FIGURE 21

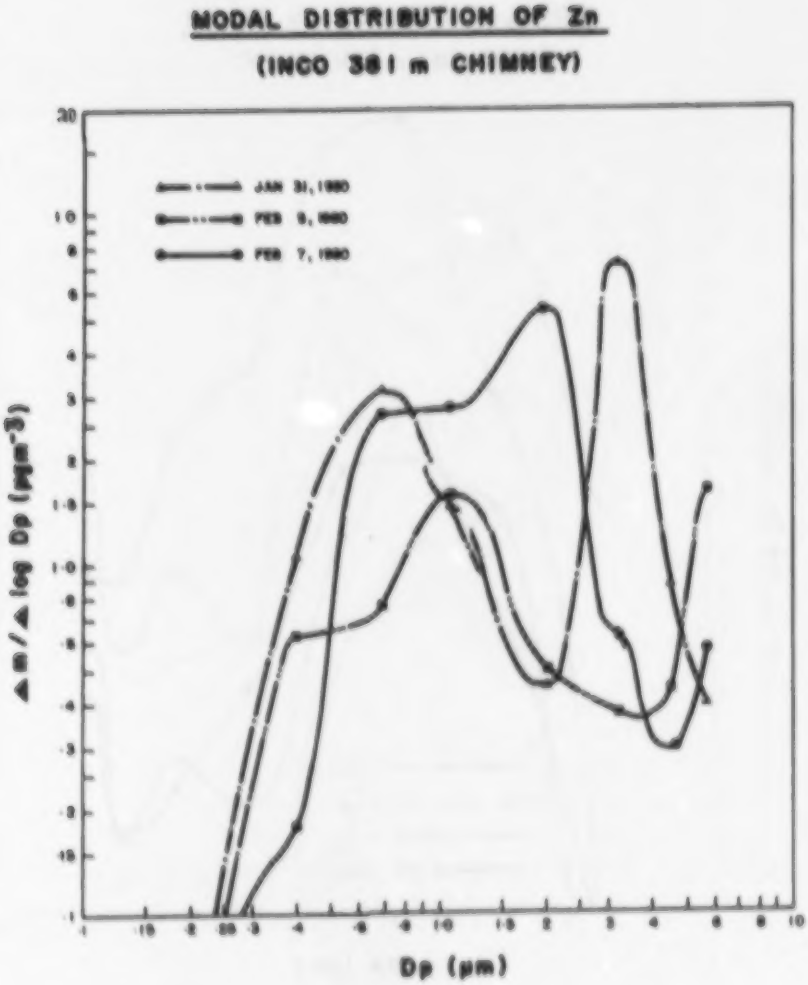

MODAL DISTRIBUTION OF Zn
(INCO 381 m CHIMNEY)
ΔB/Δ log Dp (μgm⁻³)
Dp (μm)

FIGURE 22

**MODAL DISTRIBUTION OF AE**

**(INCO 381 m CHIMNEY)**

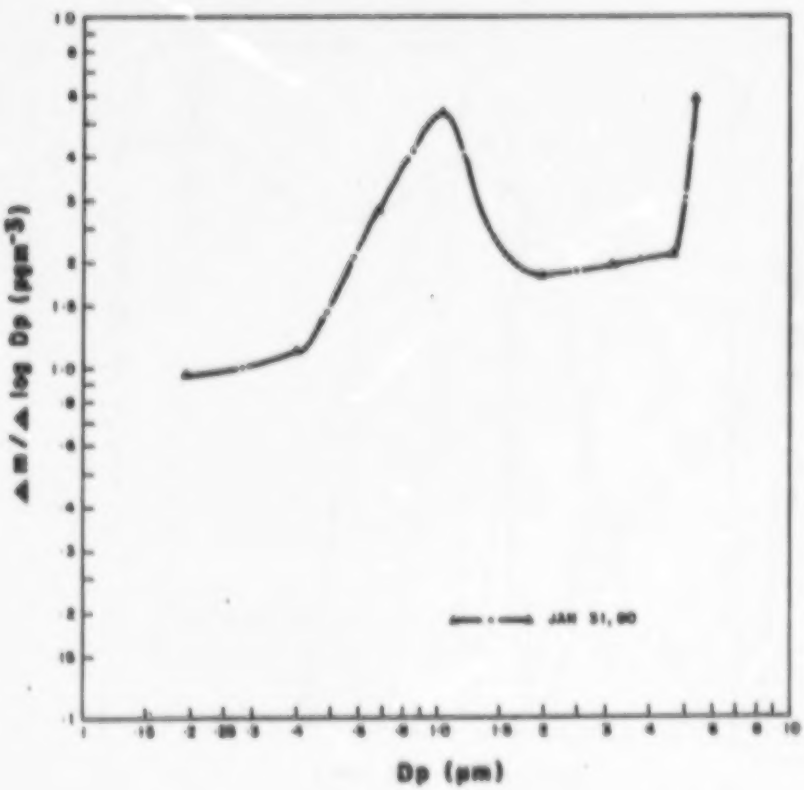


FIGURE 23

MODAL DISTRIBUTION OF Cr

(INCO 381 m CHIMNEY)

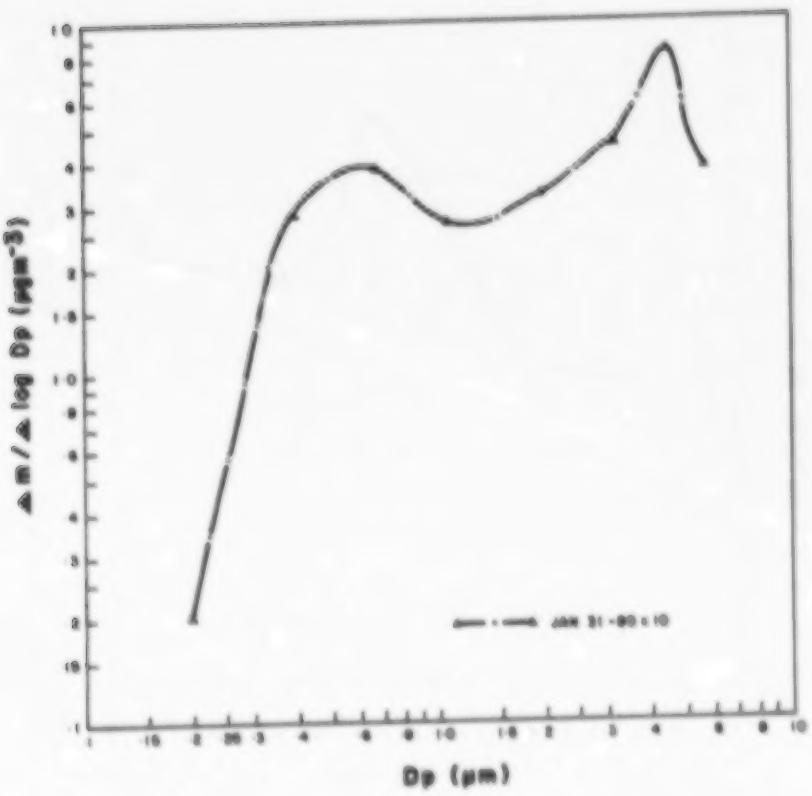


FIGURE 24

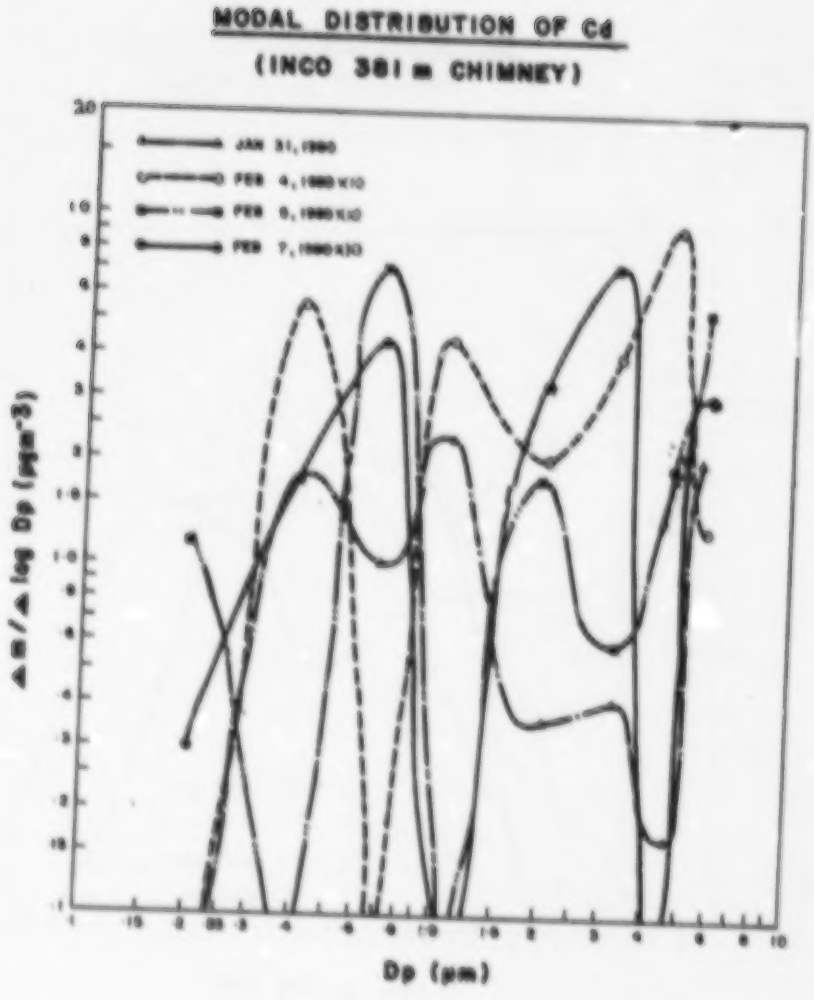

MODAL DISTRIBUTION OF Cd
(INCO 381 m CHIMNEY)
JAN 31, 1980
FEB 4, 1980 X10
FEB 5, 1980 X10
FEB 7, 1980 X10
ΔS/Δ log Dp (μgm⁻³)
Dp (μm)

FIGURE 25

**MODAL DISTRIBUTION OF Se**
**(INCO 381 m CHIMNEY)**

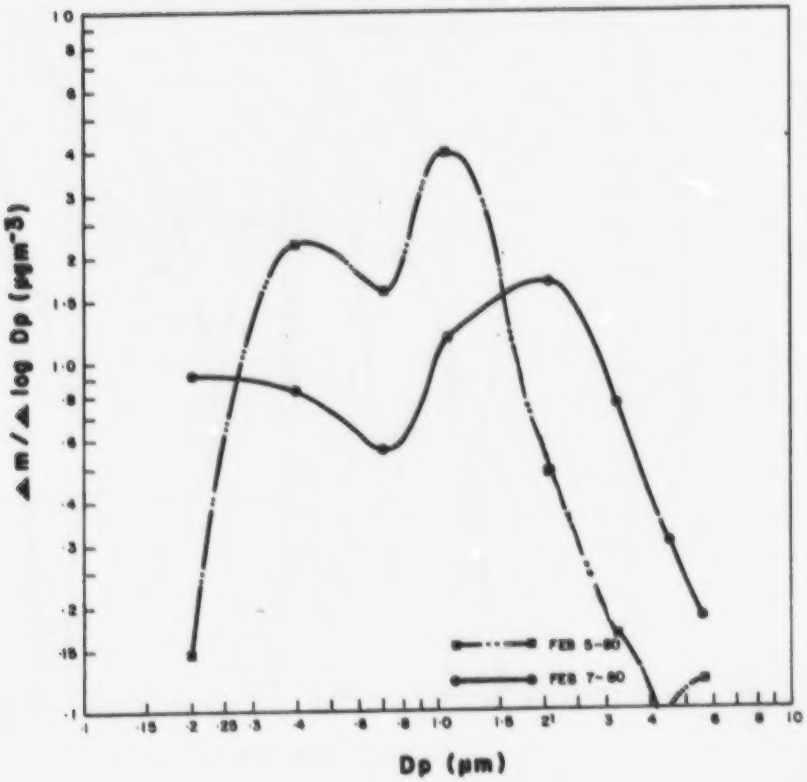


FIGURE 26

**MODAL DISTRIBUTION OF As**

**(INCO 381 m CHIMNEY)**

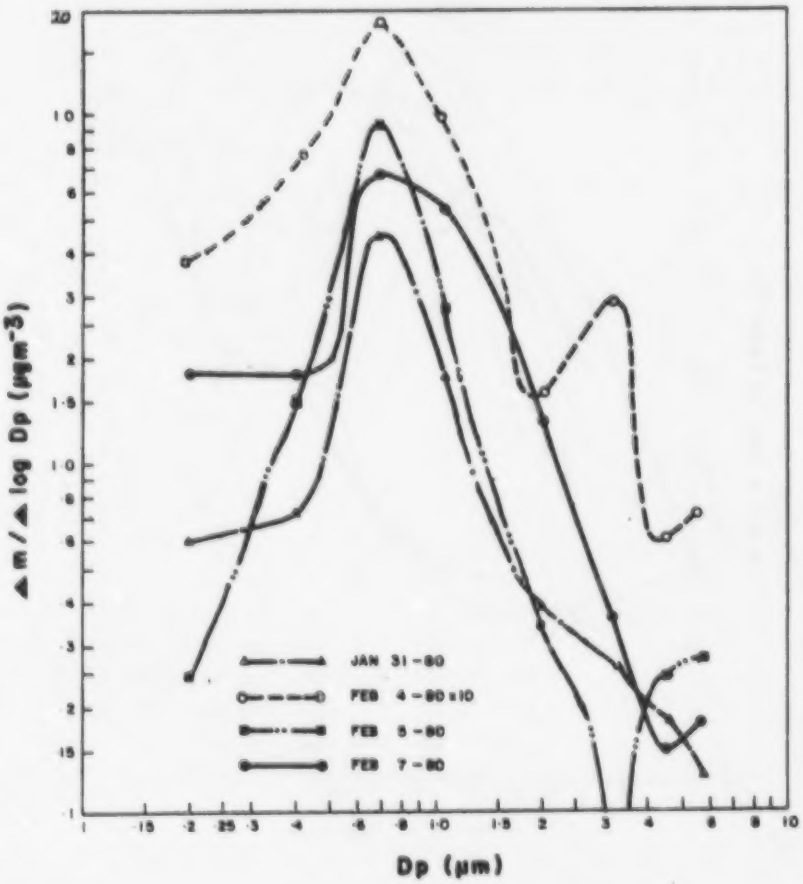


FIGURE 27

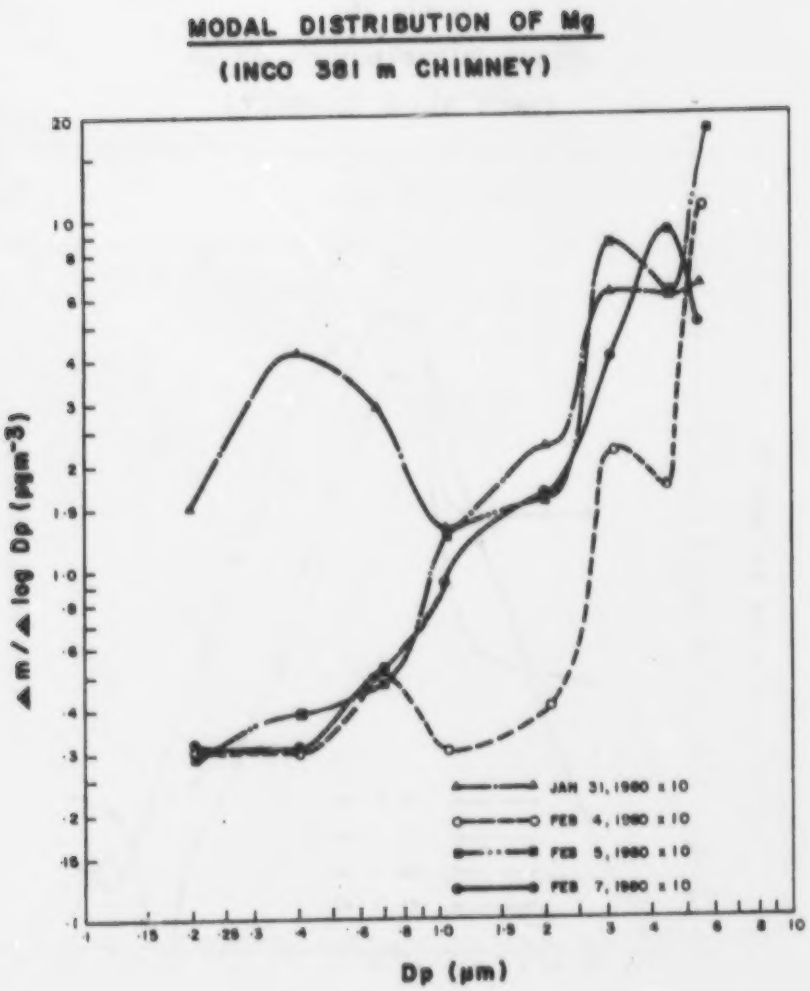

MODAL DISTRIBUTION OF Mg
(INCO 381 m CHIMNEY)
Δm/Δ log Dp (μgm⁻³)
Dp (μm)
JAN 31, 1980 x 10
FEB 4, 1980 x 10
FEB 5, 1980 x 10
FEB 7, 1980 x 10

FIGURE 28

**MODAL DISTRIBUTION OF $SO_4$**

**(INCO 381 m CHIMNEY)**

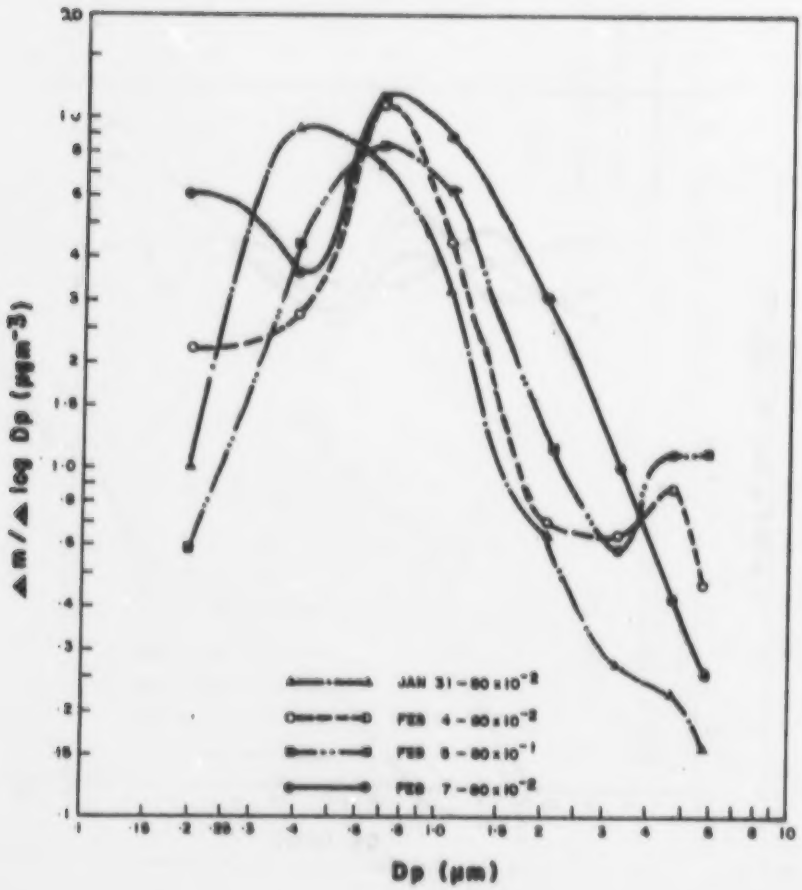
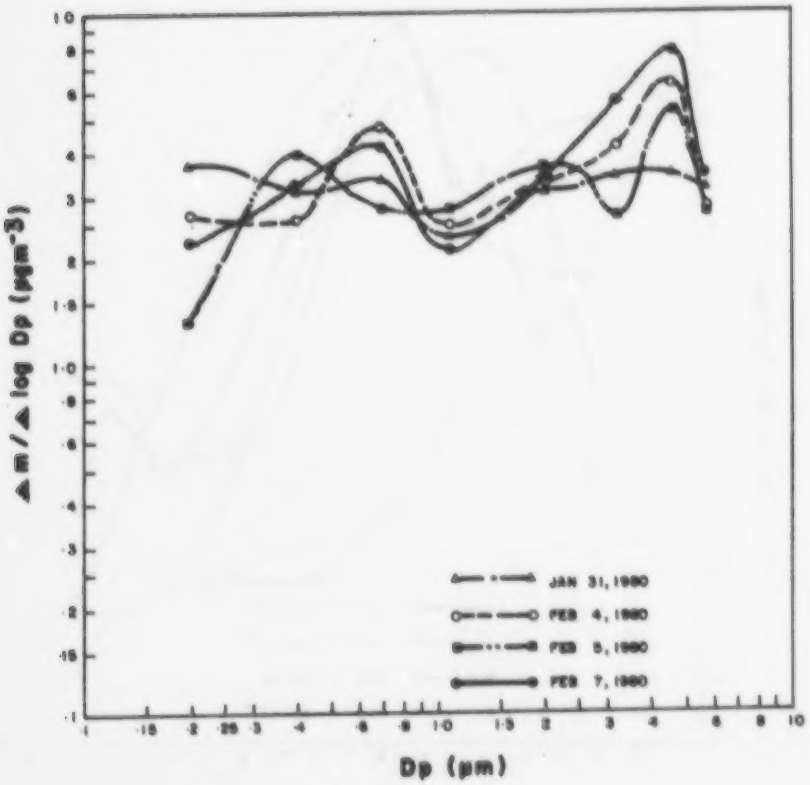


FIGURE 29

MODAL DISTRIBUTION OF $N-NH_4$

(INCO 381 m CHIMNEY)



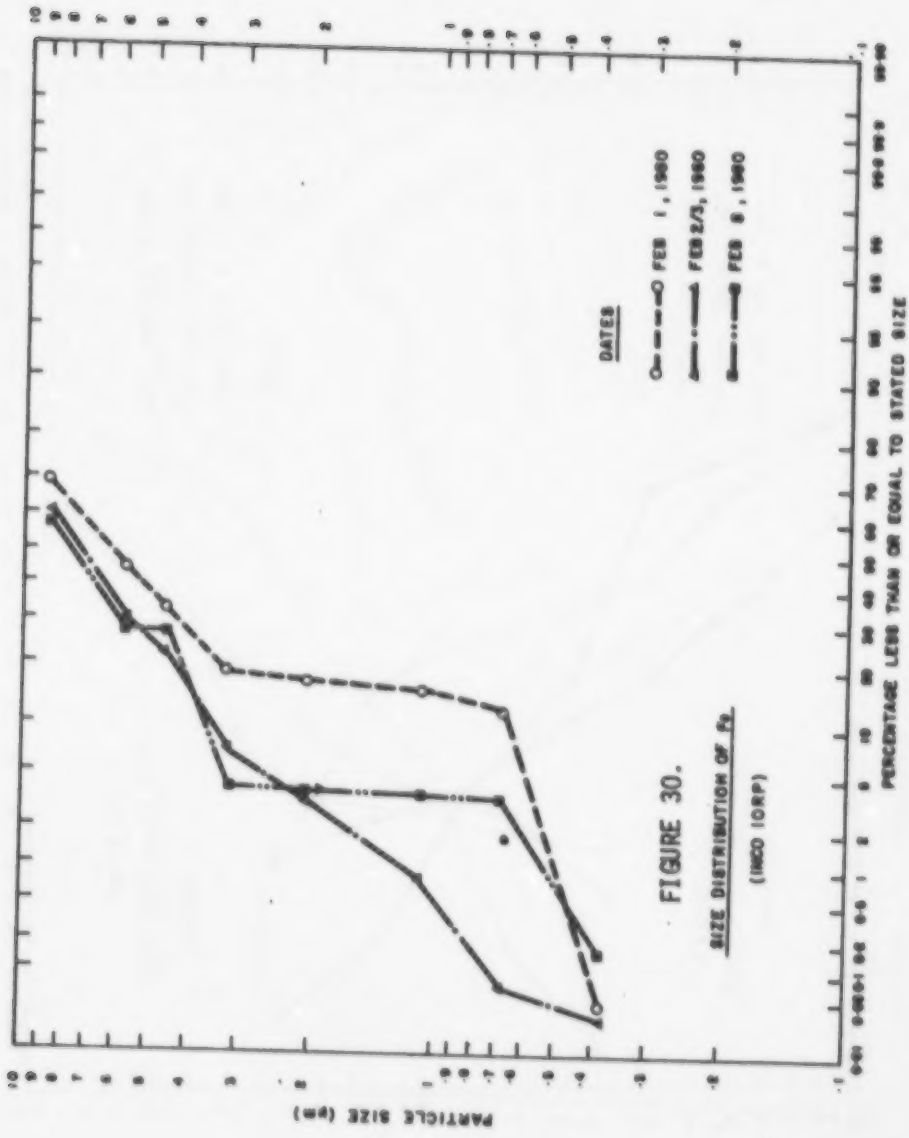



FIGURE 30.

SIZE DISTRIBUTION OF Fe

(INCO IORP)

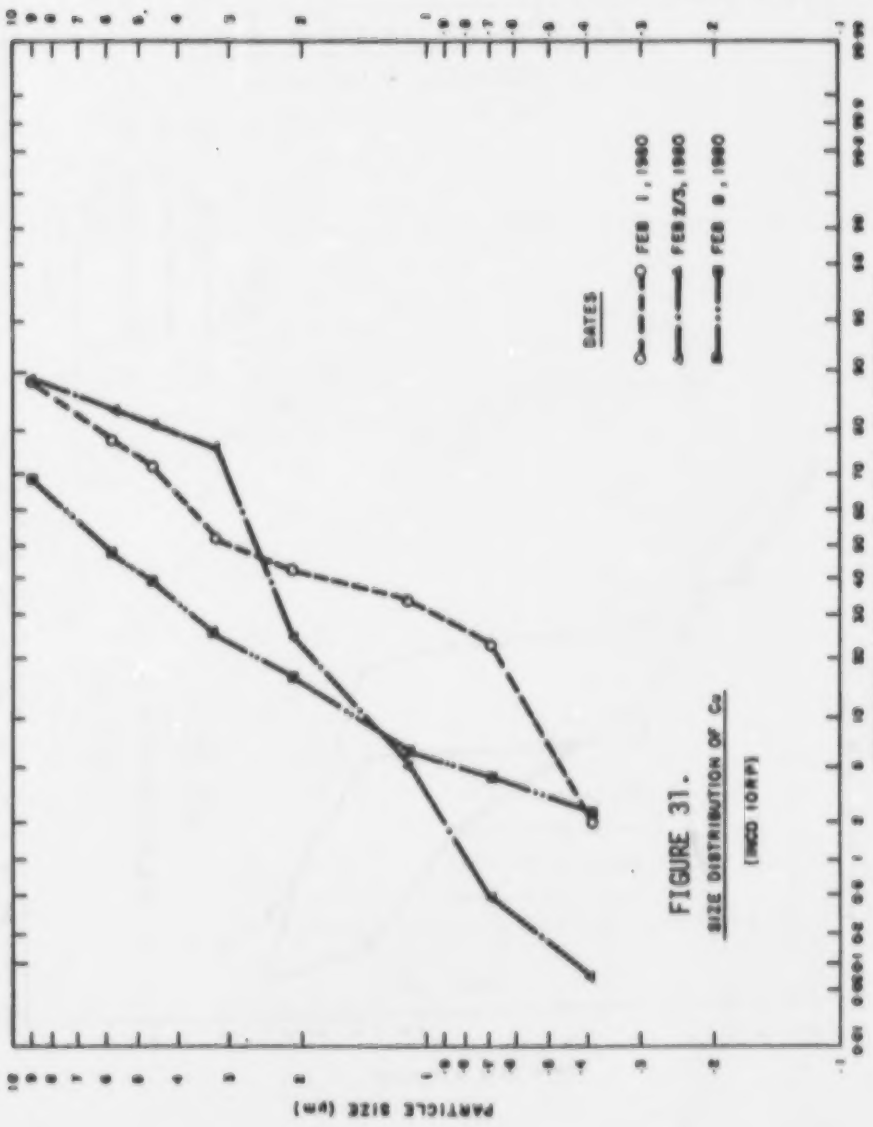



FIGURE 31.
SIZE DISTRIBUTION OF Co
(INCO 10 RP)

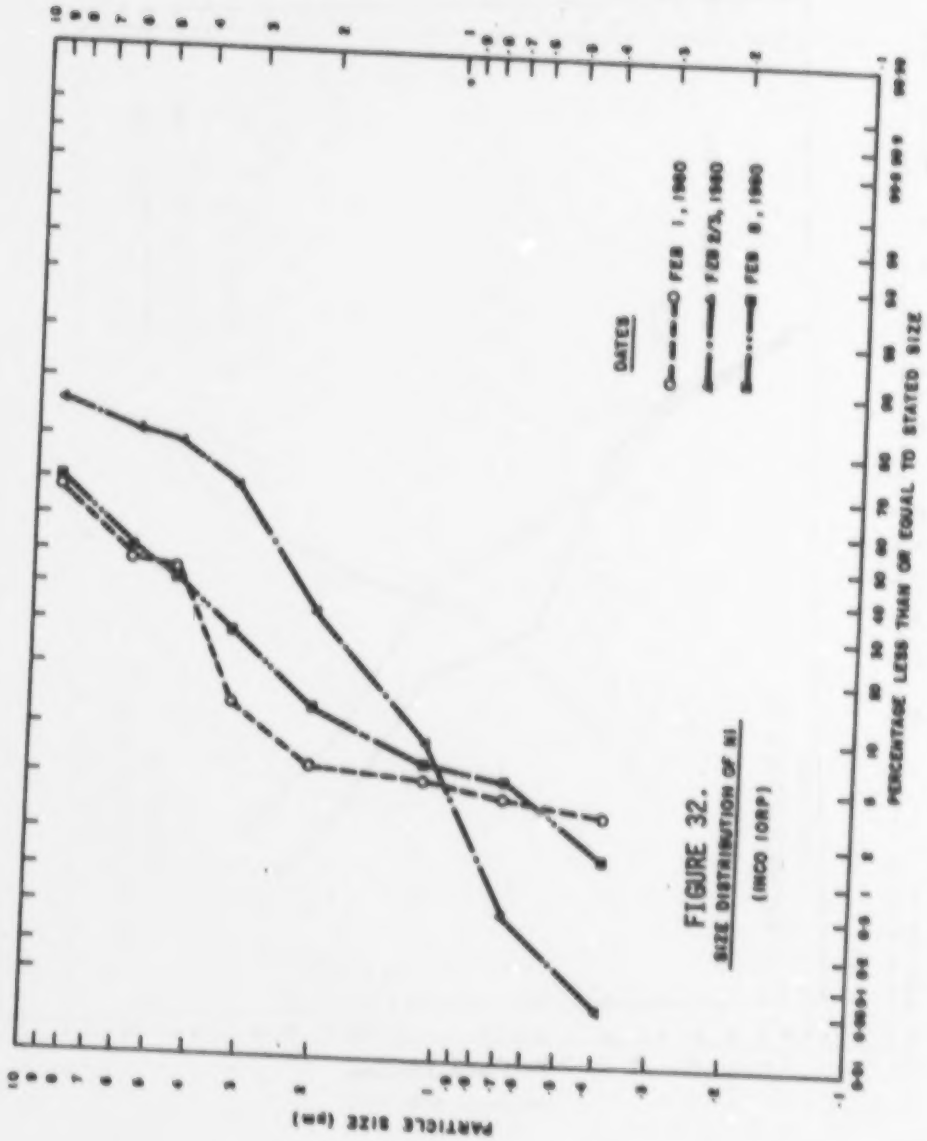



FIGURE 32.
SIZE DISTRIBUTION OF Ni
(INCO 108P)

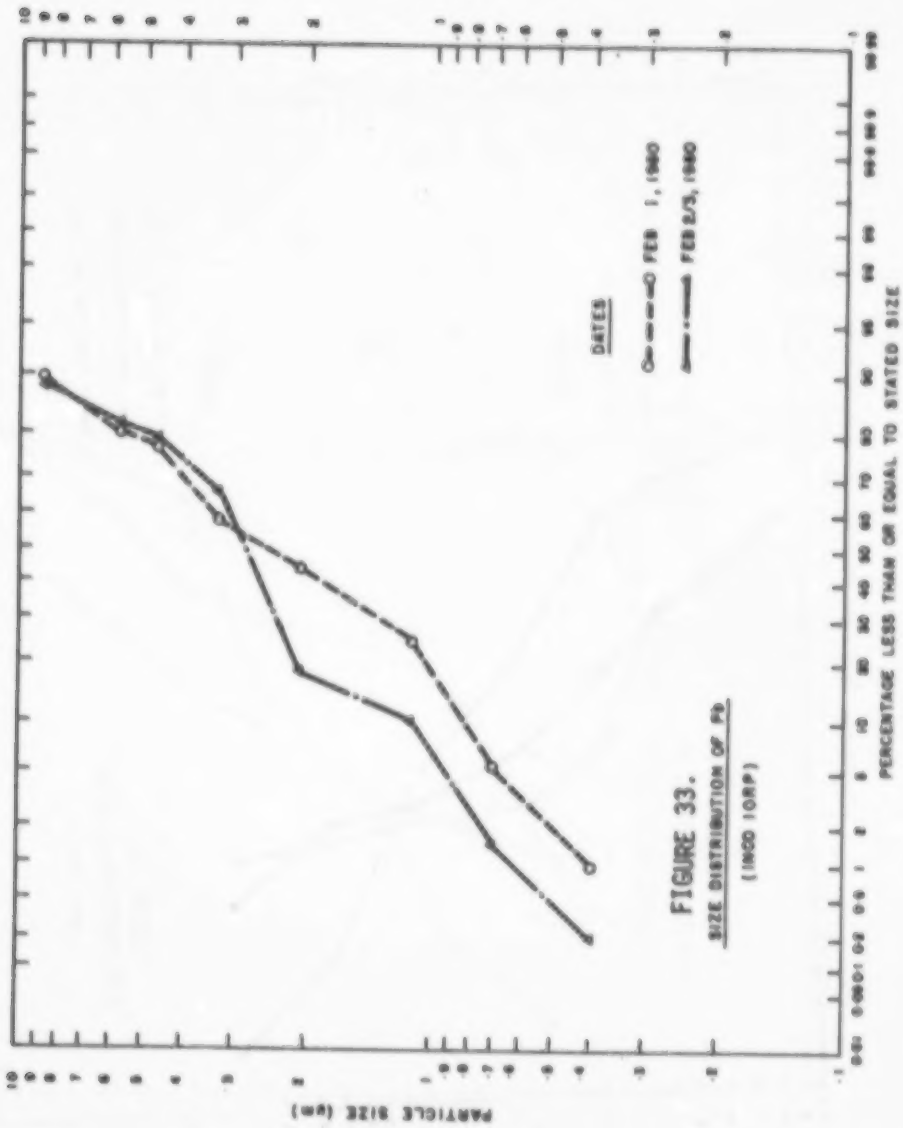



FIGURE 33.
SIZE DISTRIBUTION OF Pb
(INCO 10RP)

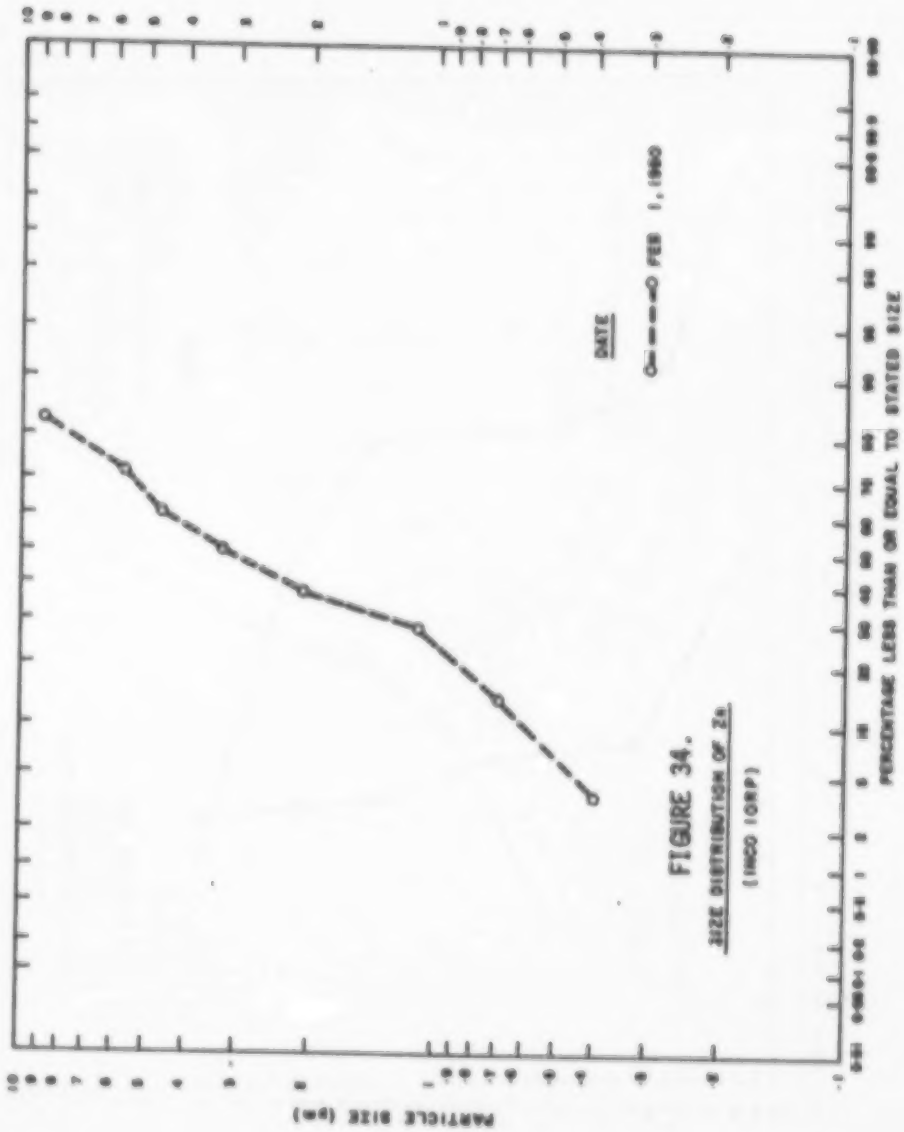



FIGURE 34.
SIZE DISTRIBUTION OF Zn
(INCO 10RP)

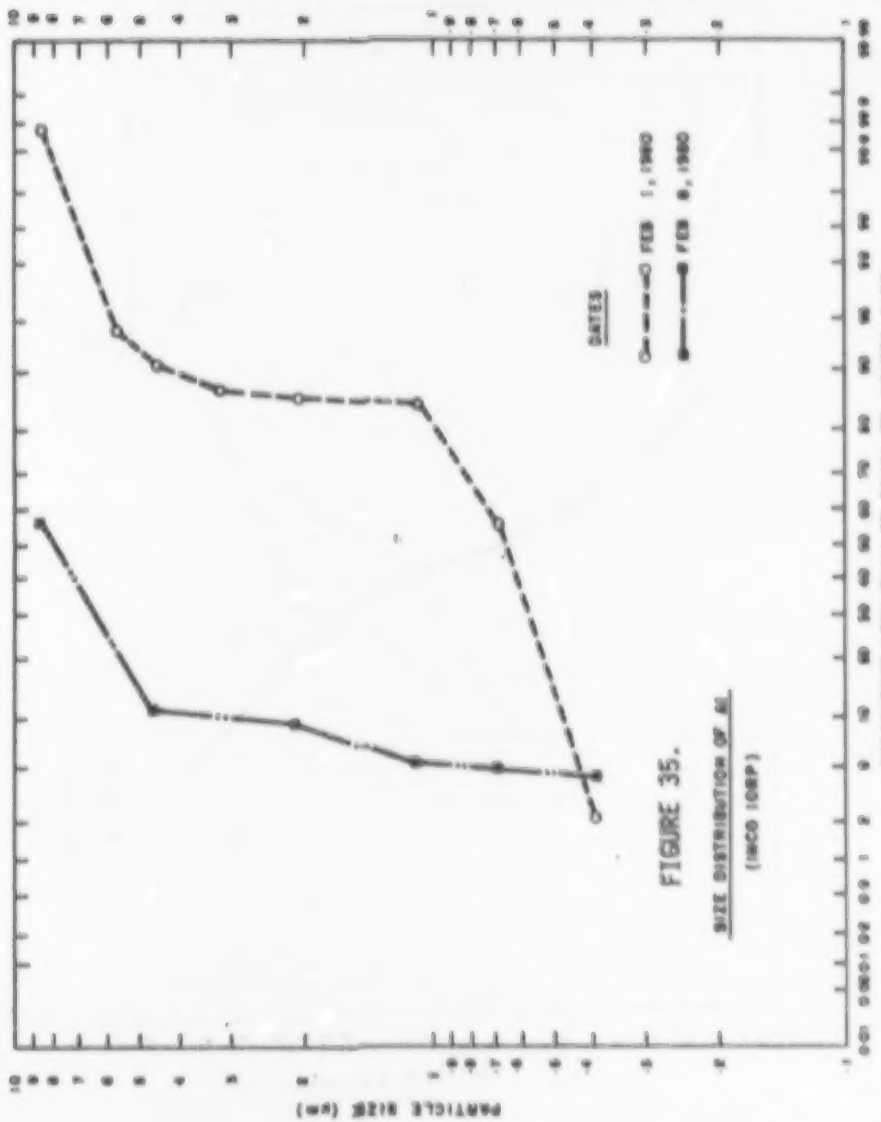



FIGURE 35.

SIZE DISTRIBUTION OF Al
(INCO 108P)

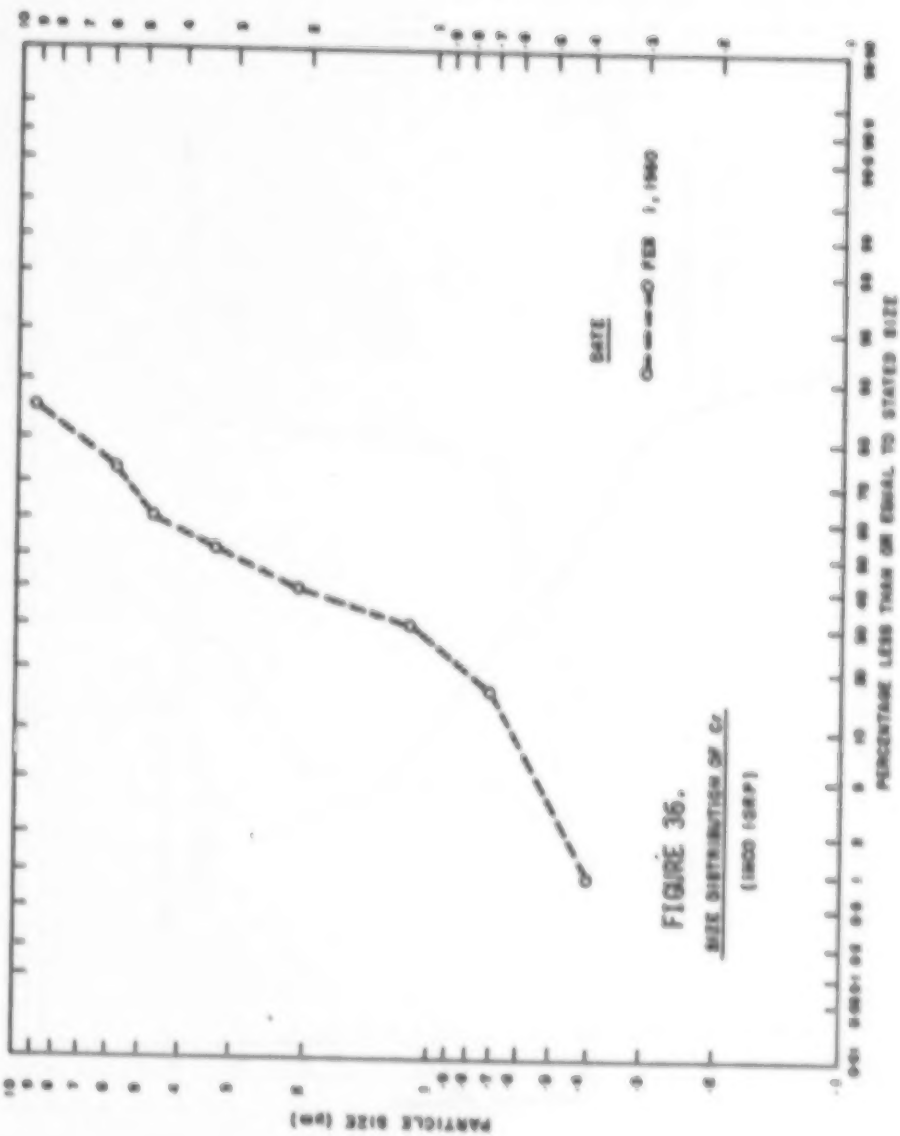

PARTICLE SIZE (μm)
DATE
FEB 1, 1980
PERCENTAGE LESS THAN OR EQUAL TO STATED SIZE

FIGURE 36.

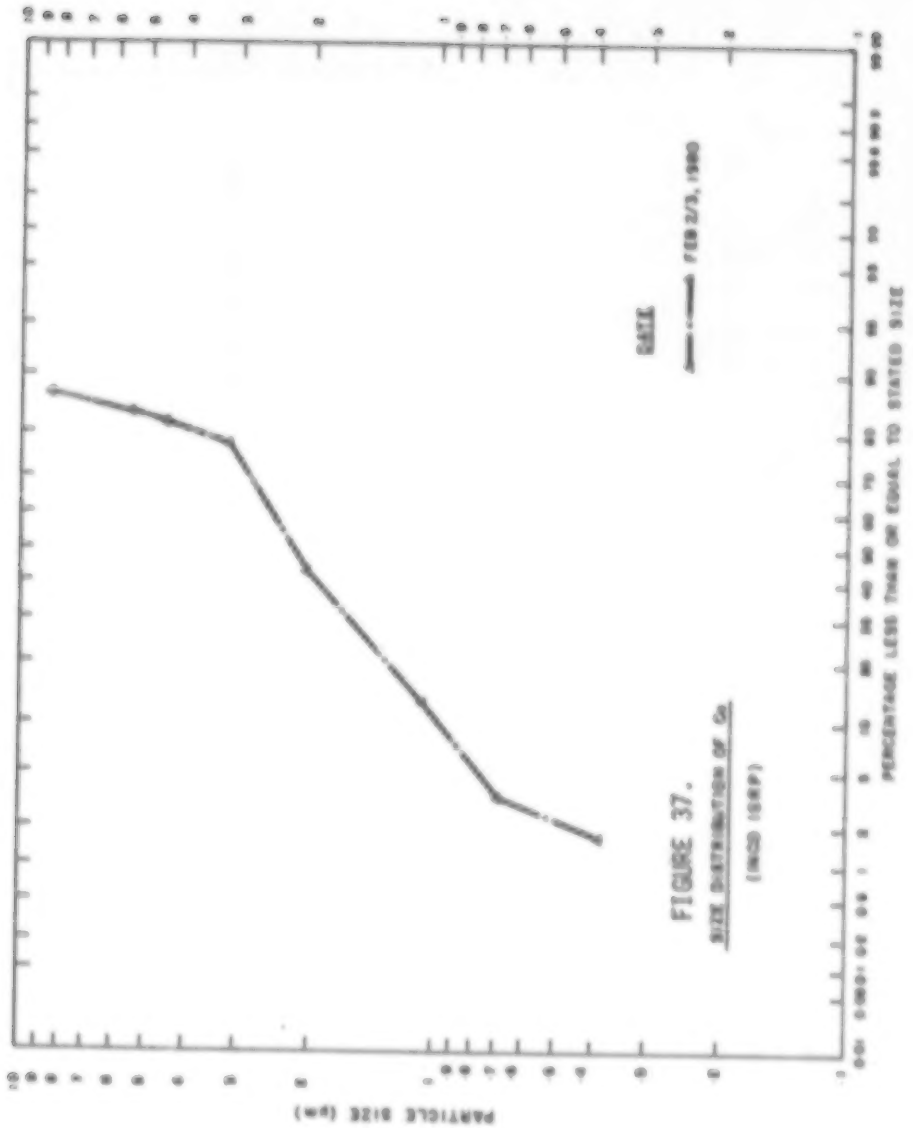



FIGURE 37.
SIZE DISTRIBUTION OF Co
(MCO (SEP)

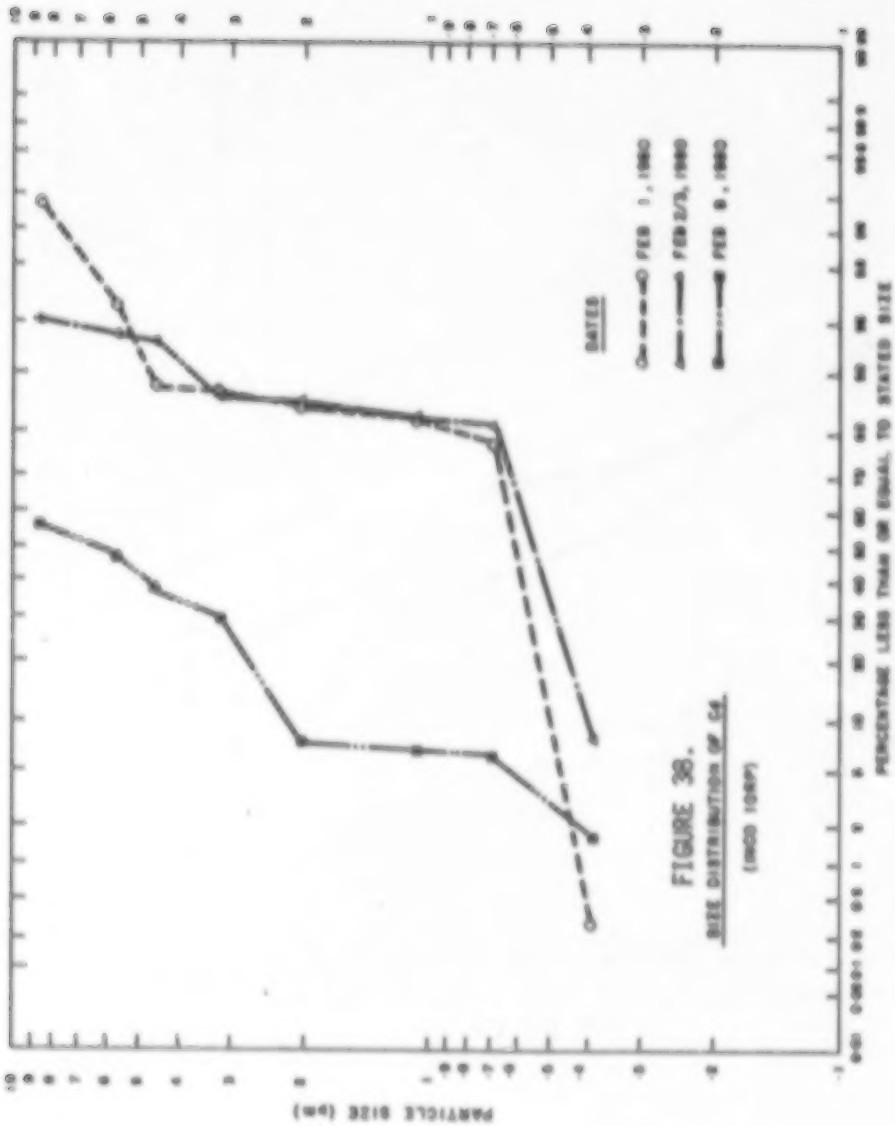



FIGURE 38.
SIZE DISTRIBUTION OF 04
(0600 1040)

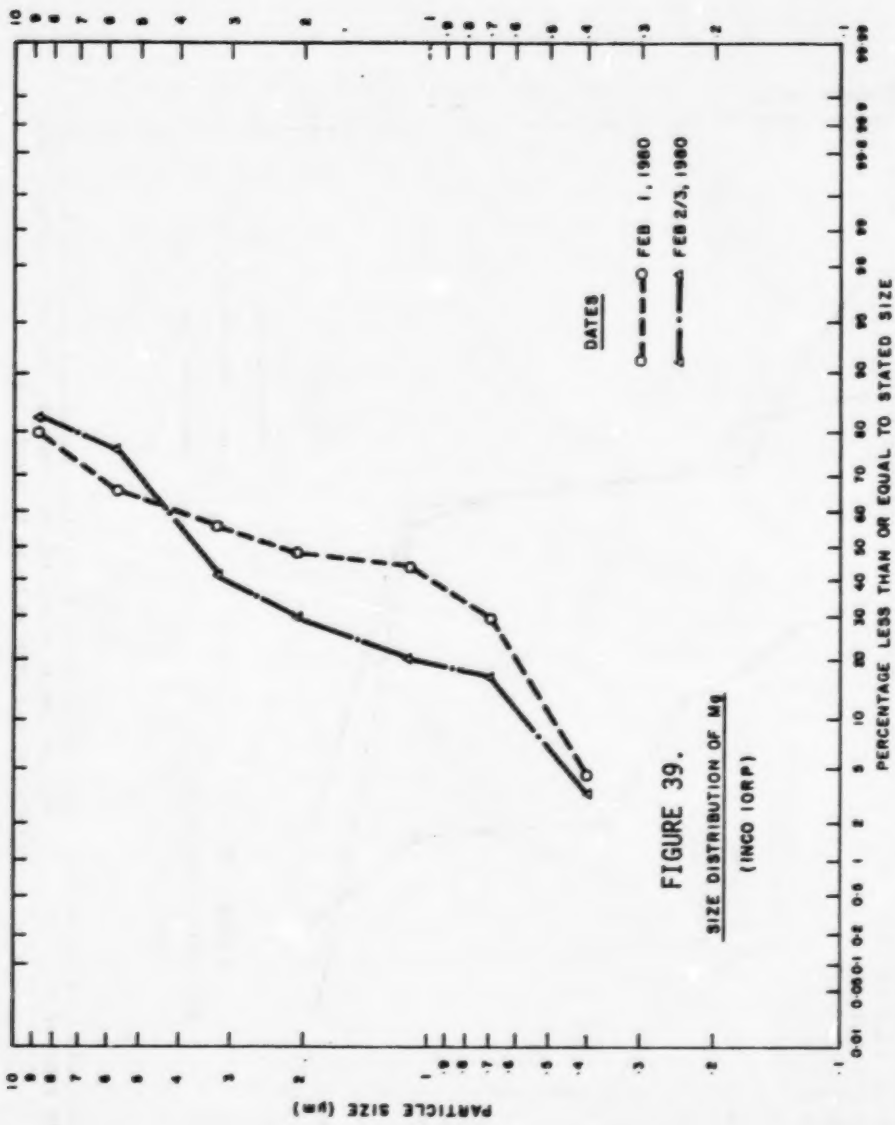



FIGURE 39.

SIZE DISTRIBUTION OF Mg

(INCO 10RP)

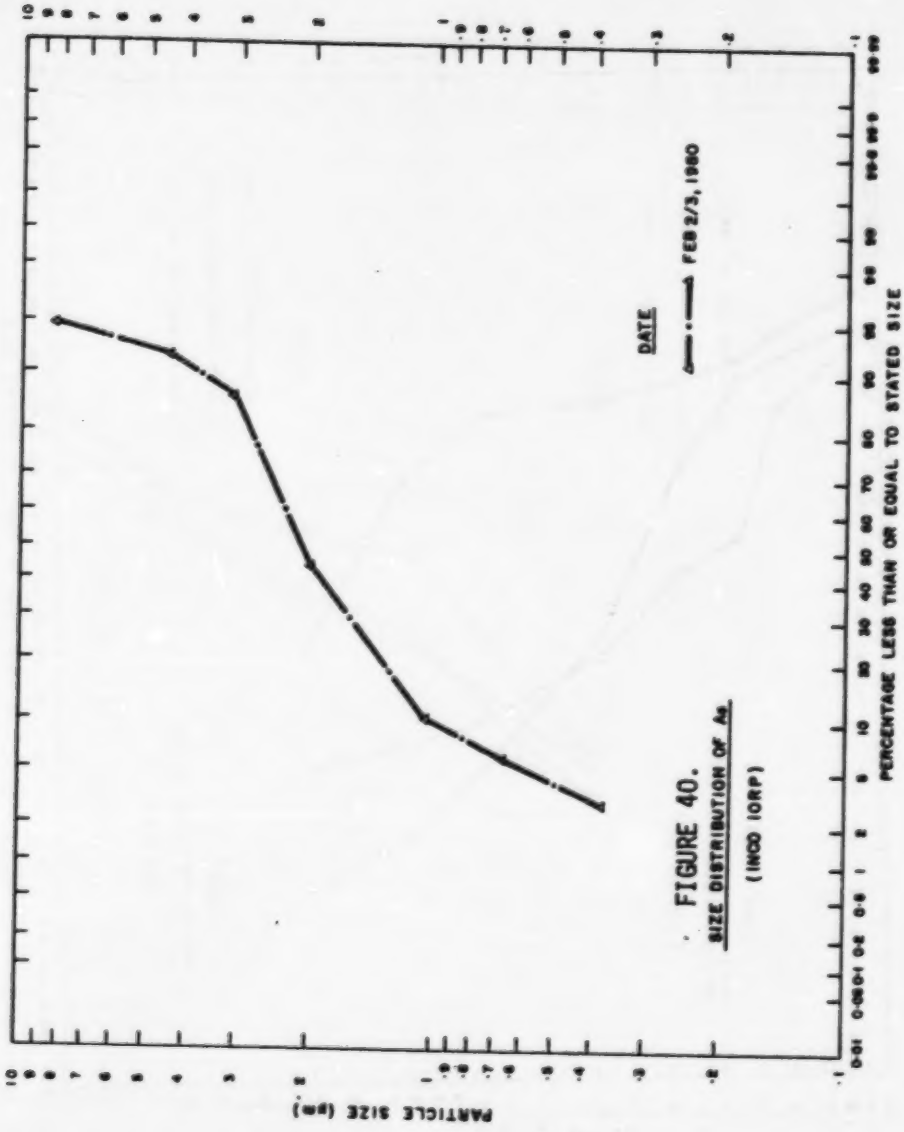



FIGURE 40.
SIZE DISTRIBUTION OF As
(INCD IORP)

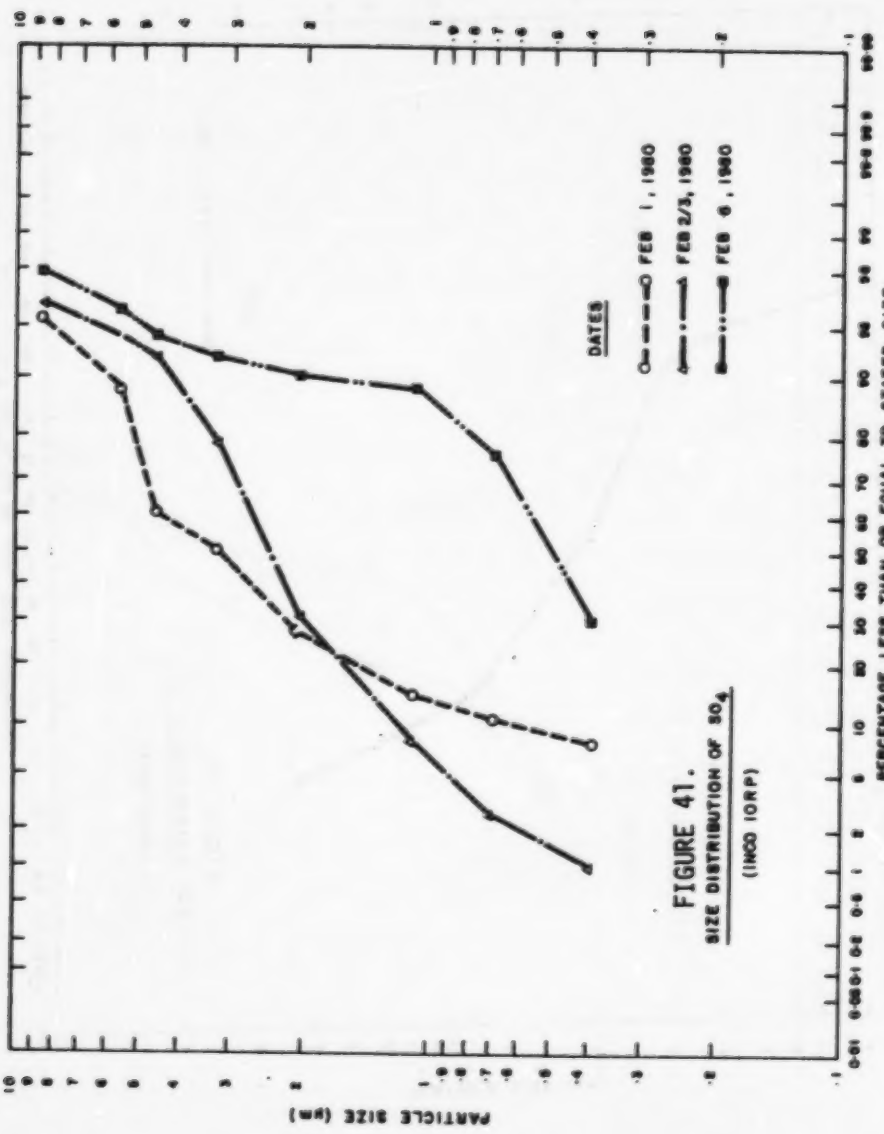



FIGURE 41.
SIZE DISTRIBUTION OF $SO_4$
(INCO 10RP)

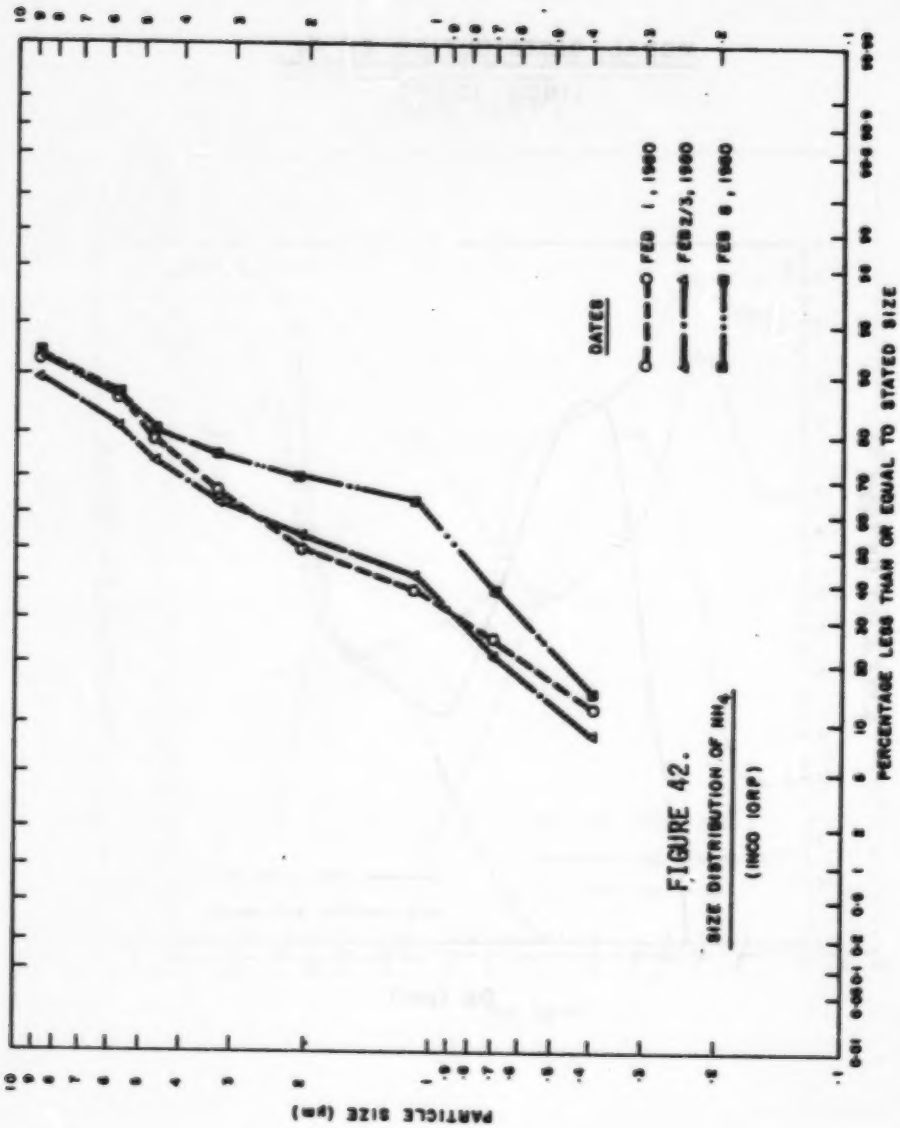



FIGURE 42.

SIZE DISTRIBUTION OF $NH_4$

(INCO IORP)

FIGURE 43

**MODAL DISTRIBUTION OF Fe**

**(INCO IORP)**

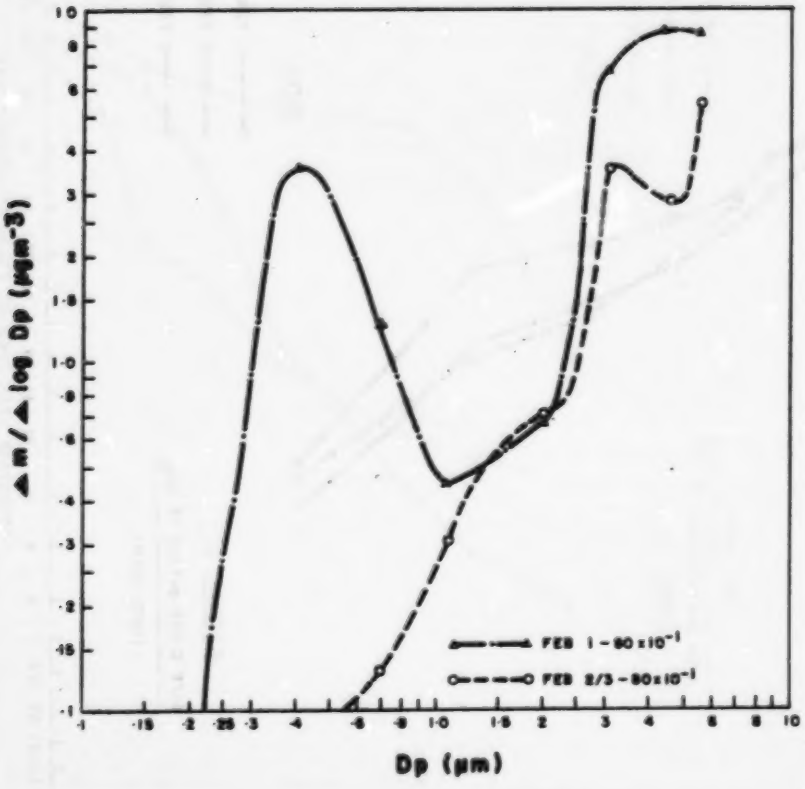


FIGURE 44

**MODAL DISTRIBUTION OF Cs**

**(INCO 1ORP)**

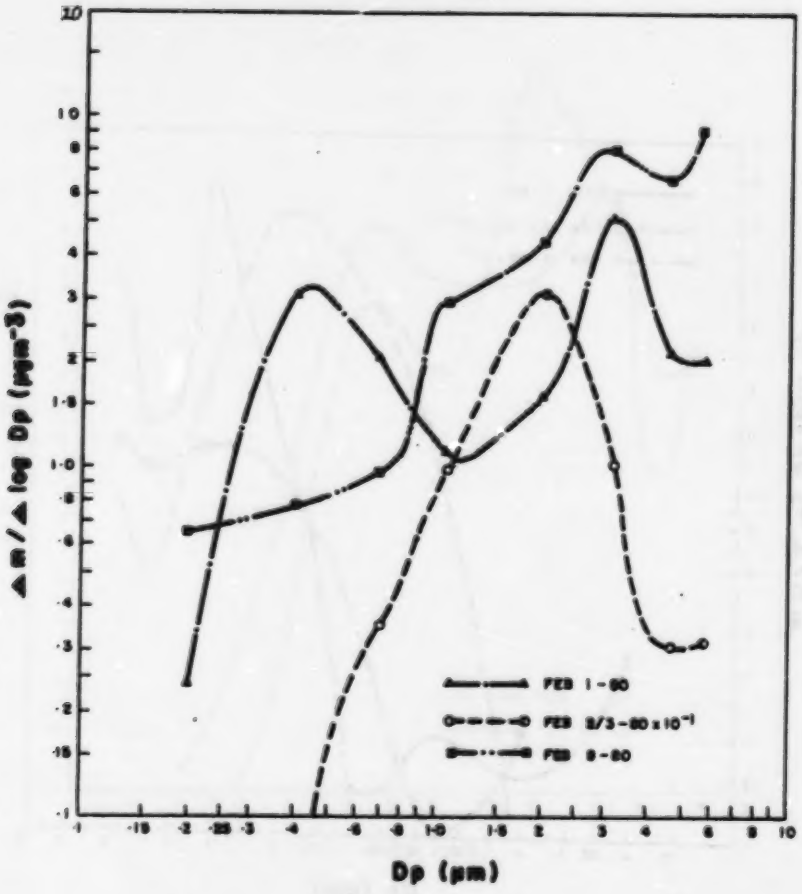


FIGURE 45

MODAL DISTRIBUTION OF NI

(INCO IORP)

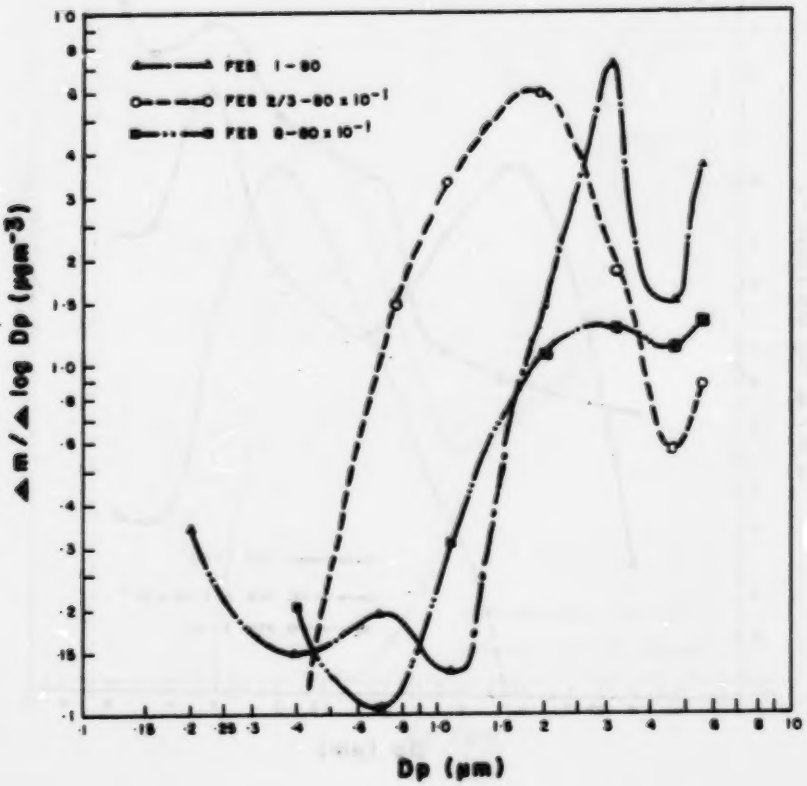


FIGURE 46

MODAL DISTRIBUTION OF Pb

(INCO IORP)

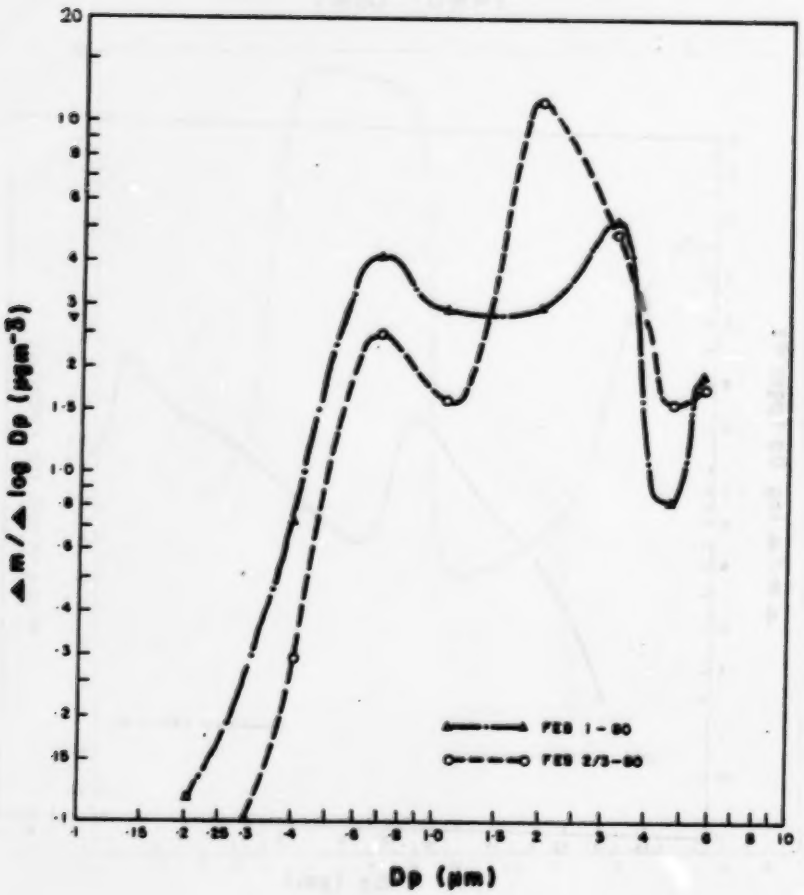


FIGURE 47

**MODAL DISTRIBUTION OF Zn**

**(INCO IORP)**

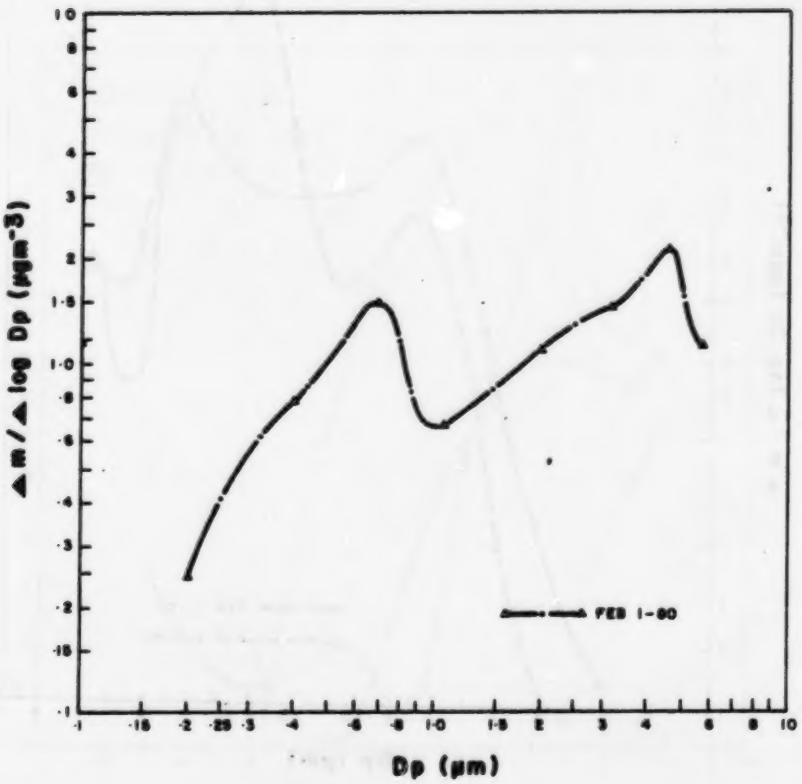


FIGURE 48

MODAL DISTRIBUTION OF Al

(INCO IORP)

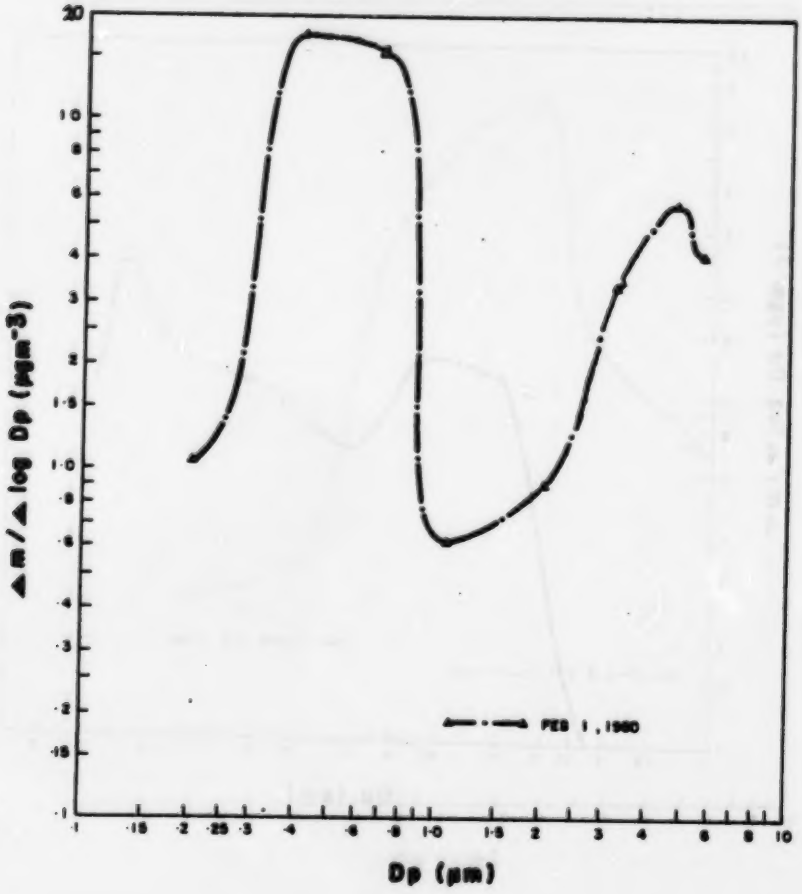


FIGURE 49

MODAL DISTRIBUTION OF Cr

(INCO IORP)

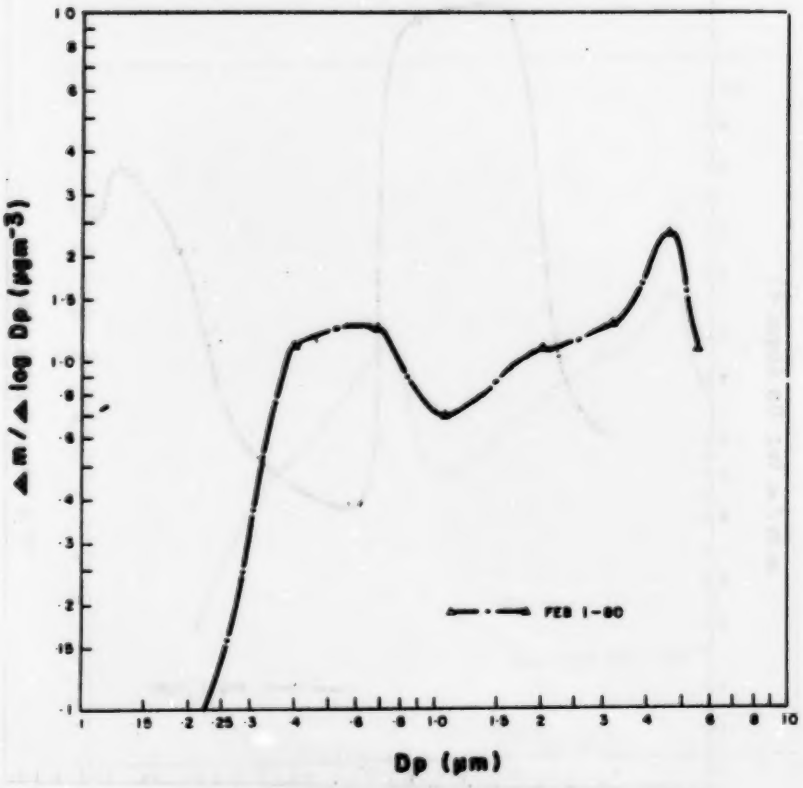


FIGURE 50

**MODAL DISTRIBUTION OF Co**

**(INCO IORP)**

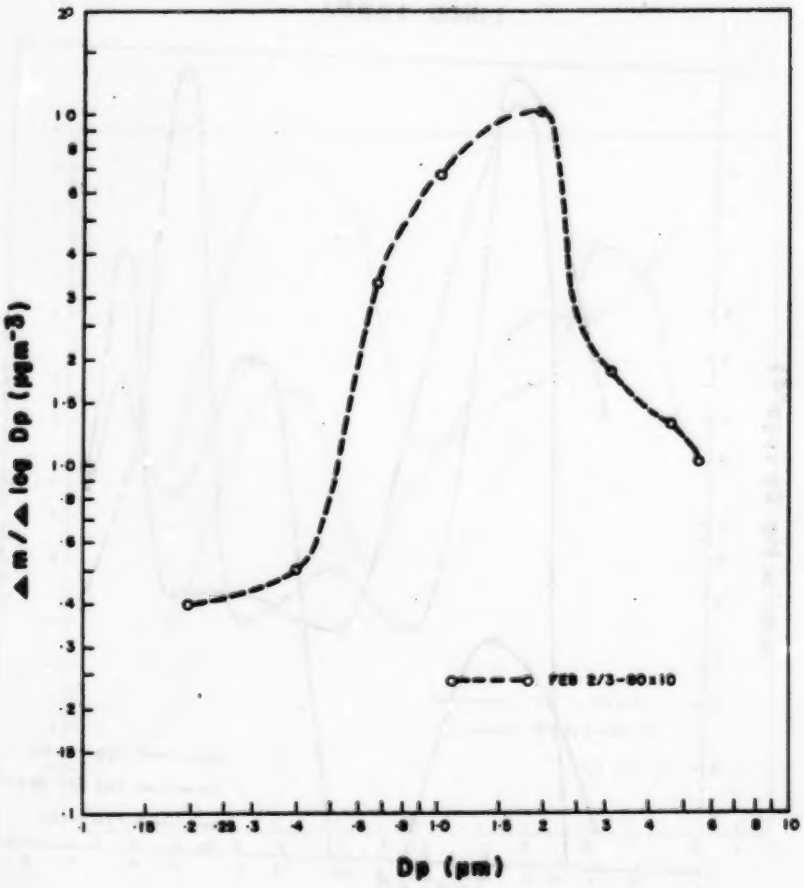


FIGURE 51

MODAL DISTRIBUTION OF Cd

(INCO IORP)

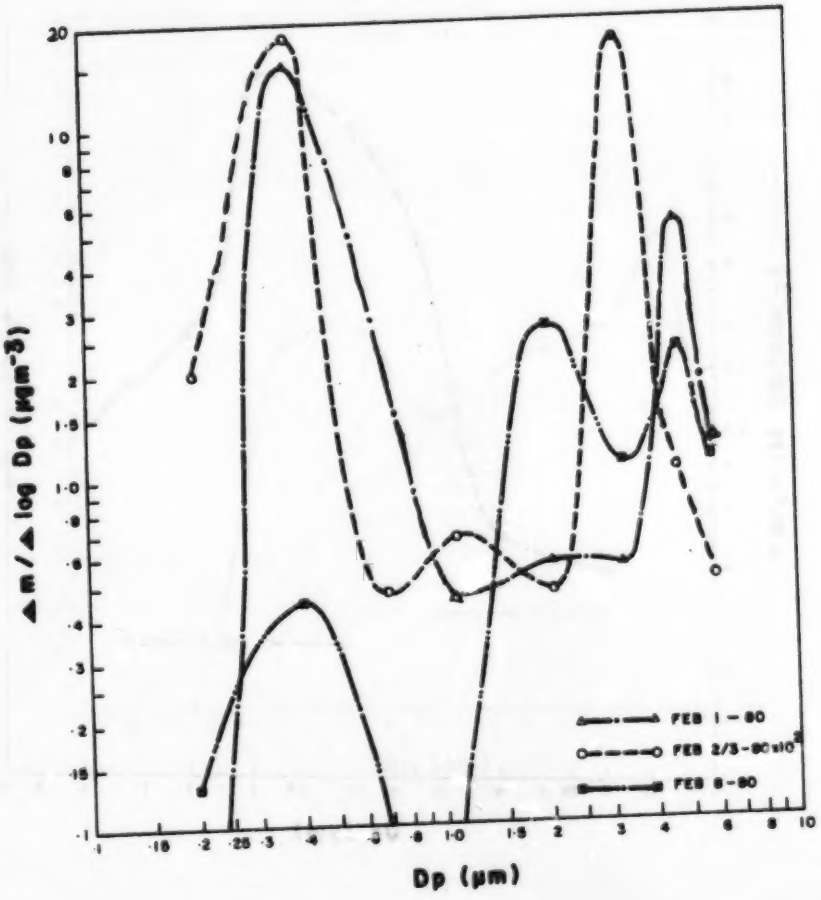


FIGURE 52

**MODAL DISTRIBUTION OF Mg**

**(INCO IORP)**

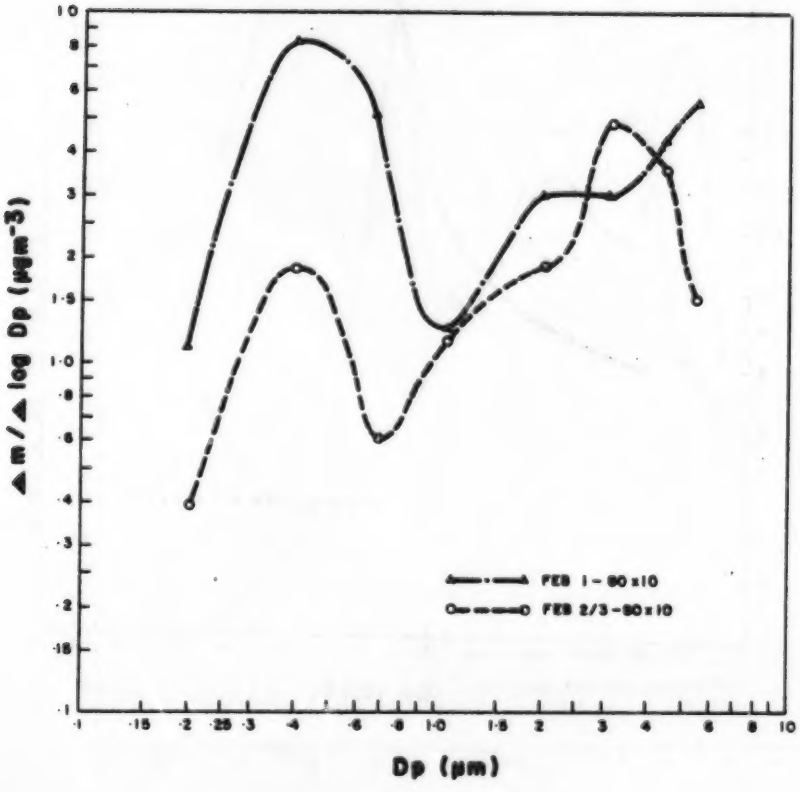


FIGURE 53

**MODAL DISTRIBUTION OF As**

**(INCO IORP)**

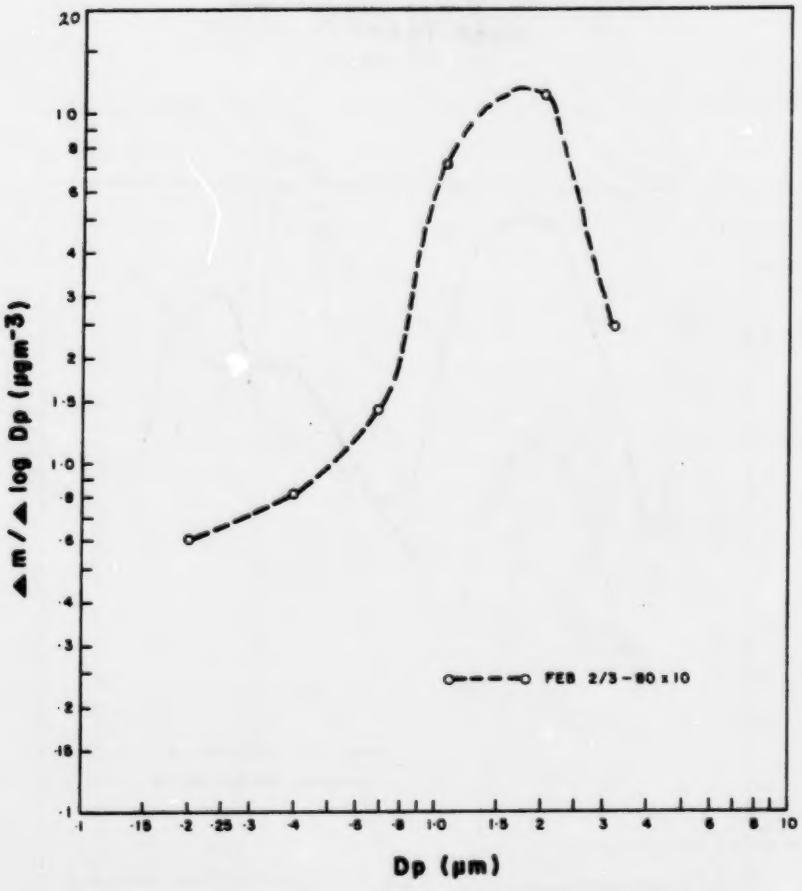


FIGURE 54

MODAL DISTRIBUTION OF $SO_4$

(INCO IORP)

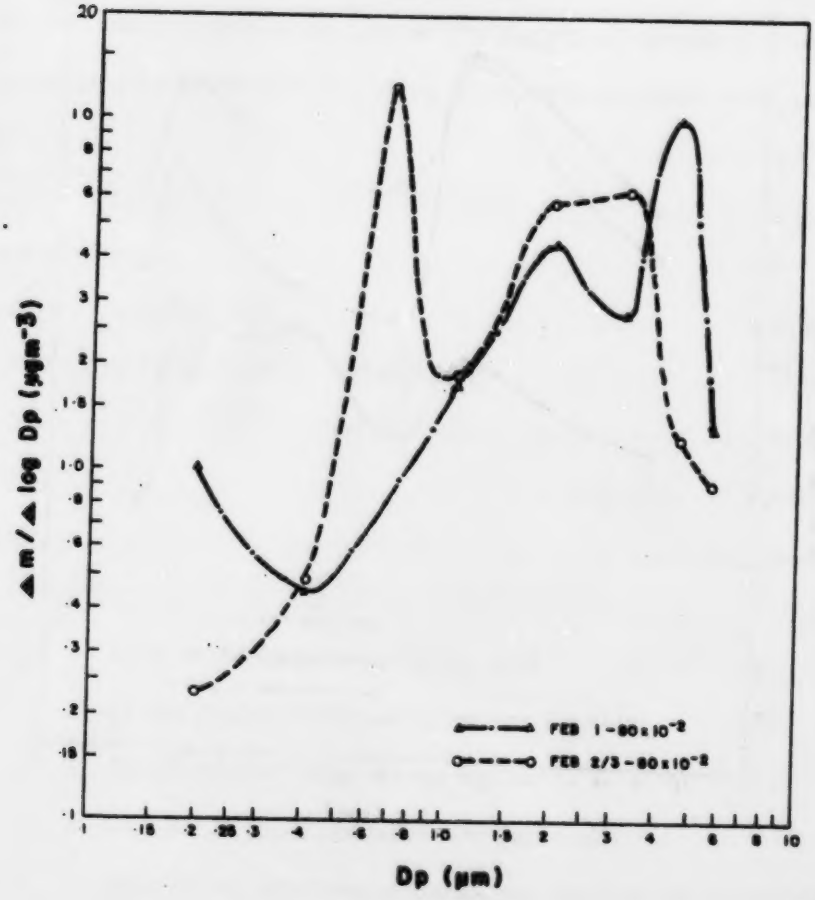
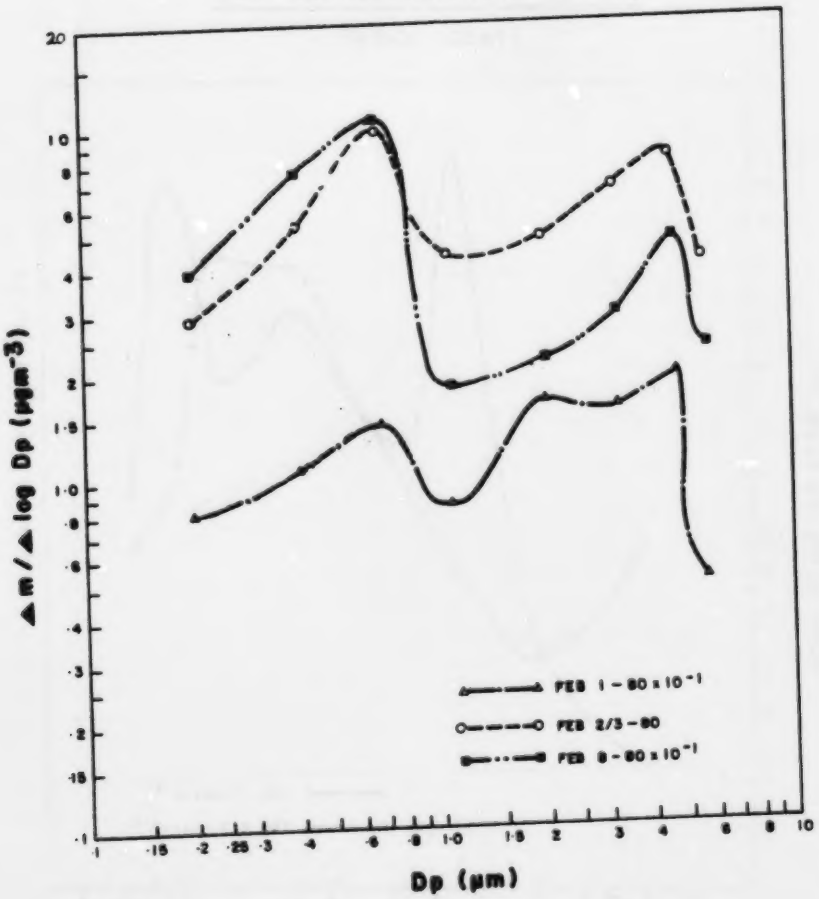


FIGURE 55

MODAL DISTRIBUTION OF N-$NH_4$

(INCO IORP)



## APPENDIX 1

### Estimates of INCO IORP Stack Emission Rates

A system of 5 linear equations was developed to equate the emission rates of the individual CCNR phases and CIL + IORP process with the total emission rates measured during individual flights. The equations assumed that the emission rate for each process was linearly dependent on the length of sampling time and the amount of material feed to the process. Also, all process emissions were assumed to be additive.

The equations are:

$$(40)\{0.89\}I + (40)\{0.92\}R = M\ Feb.\ 1_1 \quad (A1)$$

$$(78)\{0.99\}I + (52)\{1.08\}R + (49)\{0.86\}B = M\ Feb.\ 2_1 \quad (A2)$$

$$(35)\{1.09\}I + (33)\{1.02\}B = M\ Feb.\ 3_1 \quad (A3)$$

$$(54)\{1.09\}I + (46)\{1.0\}C = M\ Feb.\ 3_2 \quad (A4)$$

$$(11)\{1.09\}I = M\ Feb.\ 7_1 \quad (A5)$$

where I = IORP + CIL emission rate (kg/min)

R = CCNR REDUCTION emission rate (kg/min)

B = CCNR BLOW emission rate (kg/min)

C = CCNR CHARGE emission rate (kg/min)

M Feb. $1_1$ = Mass (in kg) of chemical parameter emitted during sampling run on day indicated - estimated by using the Ratio Method (3).

( ) = Total time in minutes that the particular process was emitting during the sampling period.

{ } = (Feed rate for date indicated)/(Average feedrate for all dates).

To illustrate the method of forming the equations, consider the day of Feb. 2, 1980 (i.e. Equation A2). The sampling period on this day was 78 minutes long. Only the IORP + CIL process operated continuously throughout the entire sampling period and the associated feedrate was 99% of the average feedrate for the 5-run field study. The concurrent CCNR REDUCTION phase was emitting for 52 of the 78 minutes with a feedrate of 108% of the average REDUCTION feedrate. The CCNR BLOW phase lasted for only 49 of the 78 minutes and the feedrate was 86% of the average BLOW feedrate. It should be noted that actual IORP + CIL feedrate data were available from INCO but CCNR feedrates were not. Instead, CCNR $SO_2$ emission rates were provided by INCO so the feedrate ratios were assumed to be equal to the $SO_2$ emission rate ratios.

Finally, the value of $M_{Feb\ 2}$ was calculated by multiplying the $M/SO_2$ ratio (obtained during that day's airborne sampling) by the $SO_2$ mass emitted during the flight.

It is apparent from the form of equations (A1) to (A5) that the following assumptions are implicit:

1. The final emission rates calculated from the equations are representative only for the average feedrate obtained during the study. For the IORP + CIL, this average feedrate was 138 MT/Day. For the CCNR, the average feedrates for the individual phases were not available so the calculated R (Reduction), B (Blow) and C (Charge) emission rates were assumed representative for average $SO_2$ emission rates of 31, 143 and 5.7 kg/min respectively.
2. The effect of increasing or decreasing the feedrate over the 5-run average feedrate was equivalent to increasing or decreasing the time of emission by the same proportionate amount.

The four unknowns in Equations (A1) to (A5), i.e. I, R, B and C can be solved using equations (A1), (A3), (A4) and (A5). The remaining equation (A2) can then be

used as a check on the goodness of the fit of the data by comparing the combined values of I, R and B against the measured emissions. Thus, the left hand side (LHS) of equation (A2) was compared to the right hand side (RHS) for each parameter of interest. The % difference equal to 100 (LHS - RHS)/RHS is shown in column 2 of Table 11.

Individual process emission rates could only be calculated for $SO_4^=$, Fe, Cu, Ni, Pb and As since these are the only parameters with sufficient data to solve the five equations. The values of $M_{Feb.\ 1}$ to $M_{Feb.\ 7}$ used in the equations are shown as Table A11 in the Appendix.

The calculated emission rates for I, R, B and C are presented in Table 11 of the text. It should be emphasized that each calculated emission rate corrresponds to only one measurement which is later checked against one other measurement (using equation A2). The good comparison between the LHS and RHS of equation (A2) suggests that the estimated emission rates are accurate within a factor of 2. However, since this is a test of several emission estimates and since the validity of the inherent assumptions is unknown, it is not possible to determine the absolute accuracy of the individual process emission rates. Notwithstanding, it does appear that the calculations provide a good first estimate of individual process emission rates which have never been measured properly using approved in-stack sampling methods.